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School of Chemical
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Muhammad Kashif Riaz

SUPPLY CHAIN ANALYSIS AND UPGRADING OF LIQUEFIED NATURAL GAS (LNG) TO MEET FINNISH GAS MARKET SPECIFICATIONS

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 19 March, 2014.

Supervisor Professor Jukka Koskinen

Instructor M.Sc. Tuomas Niskanen (Gasum Oy)

Aalto University
School of Chemical
Technology

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Muhammad Kashif Riaz

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Abstract

Liquefied natural gas (LNG) presents clean, cost-effective solution for transportation/ shipping of natural gas from remote reservoirs to consumer market. Until recently, the limits of natural gas properties, acceptable to LNG importers, had been lenient, as it was generally used for power production. However, new markets, as they use LNG to supplement their current supplies, demand an LNG with characteristics/ quality compatible to their existing pipeline grid and clientele specifications. This raises natural gas harmonization, interoperability and interchangeability issues in potential LNG importers, such as Finland which is wholly reliant on single natural gas source from Russia. Rising environmental concerns, stiffening emission regulations and energy security drive Finland to import LNG.

This thesis is aimed at identifying the world LNG sources suitable for import to Finnish market based on specifications required by natural gas applications in Finland. The thesis also studies the LNG value chain in general and the LNG quality modification at import terminal/ regasification plant.

Production, liquefaction, storage, transportation, and regasification are core components of LNG value chain besides numerous minor constituents including LNG liquid fuel engines. Finnish natural gas market is divided into broad segments of traffic, off-grid industry and existing gas grid users. Specification-data of all three designated sectors was collected from the manufacturers and industry. By considering three interchangeability parameters of natural gas: methane number, Wobbe index (lower), and lower heating value, this data was mapped on charts to determine the requirement of each sector and finally the common demand band (common window) of all the sectors. Similarly, the data of 27 available LNG sources and 3 European LNG re-export terminals was gathered and graphically analyzed. A preliminary simulation of 3 alternative processes, by means of Aspen HYSYS software, and their subsequent comparison resulted in selection of LPG Extraction as the most feasible LNG de-richment technique employed at a receiving terminal LNG re-vapourization plant.

As per the current Finnish market requirement and grid conditions, out of 27 global LNG sources, the number of feasible sources remains 3; however, it could be increased to 7 by compromising land traffic sector methane number demand, and to 11 if the upper bounds for heating value are relaxed up to +3%. LNG from rest of the producers can be viable with additional processing at the targeted market in Finland.

Keywords LNG, methane number, LNG quality, natural gas interchangeability, gas quality harmonization, calorific value, Wobbe index, LNG quality upgradation, LNG engines, Finnish LNG market, LNG specifications, natural gas economy, LNG economy, LNG import terminal, LNG quality adjustment, LNG value chain, de-richment Aspen HYSYS model, heating value reduction, nitrogen ballasting, LPG extraction from LNG, NGL removal from LNG.

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List of Abbreviations

AAV	: Ambient Air Vaporizer
AGA	: American Gas Association
ANG	: Adsorbed Natural Gas
APG	: Associated Petroleum Gas
ASTM	: American Society for Testing and Materials
BOG	: boil-off gas
CARB	: California Air Resources Board
CEN	: Comité Européen de Normalisation
CNG	: Compressed Natural Gas
CHP	: Combined Heat and Power
CWHE	: Coil-wound Heat Exchanger
EC	: European Commission
ECA	: Emission Control Area
EN	: Europäische Norm (European Standard)
EOS	: Equation of State
EU	: European Union
FLNG	: Floating Liquefaction of Natural Gas
FPSO	: Floating Production, Storage and Offloading
FSRU	: Floating Storage and Regasification Unit
GERG	: European Gas Research Group
GHG	: Green-house Gas
GRI	: Gas Research Institute
HC	: hydrocarbon
HDV	: heavy-duty vehicle
HFO	: Heavy Fuel Oil
HHV	: higher heating value
ICE	: Internal Combustion Engine
IFV	: Intermediate Fluid Vaporizer
IMO	: International Maritime Organization
ISO	: International Organization for Standardization
LHV	: lower heating value
LIN	: liquid nitrogen
LNG	: Liquefied Natural Gas
LPG	: Liquefied Petroleum Gas

MARPOL	: Marine Pollution (International Convention for the Prevention of Pollution from Ships)
MRC	: Mixed Refrigerant Cycle
MCHE	: Main Cryogenic Heat Exchanger
MCR	: Multi-component Refrigerant
MDO	: Marine Diesel Oil
MN	: Methane Number
MON	: Motor Octane Number
MWI	: Modified Wobbe Index
NG	: Natural Gas
NGL	: Natural Gas Liquids
NGV	: Natural Gas Vehicle
NMHC	: non-methane hydrocarbons
NO_x	: oxides of nitrogen
OECD	: Organization for Economic Cooperation and Development
OEM	: Original Equipment Manufacturer
ORV	: Open Rack Vaporizer
PM	: particulate matter
QC	: Quality Control
RCC	: Reinforced Cement Concrete
RD	: relative density
RON	: Research Octane Number
SAE	: Society of Automotive Engineers
SECA	: Sulphur Emission Control Area
SCV	: Submerged Combustion Vaporizer
STV	: Shell and Tube Vaporizer
SOP	: Standard Operating Procedure
SO_x	: oxides of sulphur
SG	: specific gravity
SI	: Spark Ignition
THC	: Total Hydrocarbons
TPES	: Total Primary Energy Supply
UNECE	: United Nations Economic Commission for Europe
vs	: versus
WI	: Wobbe Index
WN	: Wobbe Number
WQA	: Wobbe Quality Adaptation

List of Symbols

atm	: atmospheric pressure
Avg.	: average
bara	: bar (absolute)
barg	: bar (gauge)
btu	: British Thermal Unit
BCM	: billion cubic meters
H/C	: hydrogen to carbon ratio
Max.	: maximum
Min.	: minimum
MMCM	: million cubic meters
MT	: million tonnes
MTPA	: million tonnes per annum
Nm^3	: Normal cubic meter (i.e., defined at 0 °C, 1.01325 bar)
ppbw	: parts per billion by weight
ppmv	: parts per million by volume
ppmw	: parts per million by weight
psia	: pound per square inch (absolute)
scf	: standard cubic foot
Sm^3	: standard cubic meter
TWh	: tera watt hour
$\sqrt{b}$	: Summation factor
d	: Relative density
$\widetilde{H}$	: Calorific value on volumetric basis
M	: Molar mass
p	: Pressure (absolute)
R	: Molar gas constant (=8.314510 $J.mol^{-1}. K^{-1}$)
t	: Temperature in Celsius
T	: Absolute (thermodynamic) temperature
V	: Volume
W	: Wobbe index
x	: Mole fraction
Z	: Compression factor
ϕ	: Equivalence Ratio

ρ : Mass density

% : percent

$>$: Greater-Than

$\geq$: Greater-Than or Equal To

$<$: Less-Than

$\leq$: Less-Than or Equal To

Subscripts

air : For air

i : Identifier of a particular value in a set

I : Inferior (for LHV)

j : Component identifier

mix : For the mixture or gas

S : Superior (for HHV)

1 : For the combustion reference conditions

2 : For the volumetric or metering reference conditions

Superscripts

$\circ$: For the ideal gas state (no superscript indicates real-gas state)

n : Number of component in a mixture

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1. Introduction

Natural gas occupies a significant place in the current global energy scenario as the cleanest available fossil fuel (Wang & Economides, 2009) (Economides & Wood, 2009) (NaturalGas.org , 2011). Numerous factors, such as high fluctuations of fossil oil prices, the close link between oil price and political stability in the Western countries as well as its high environmental impact, have led researchers to consider large-scale fuel alternatives. In terms of both economic and ecological measures, natural gas has proved to be a competitive alternative to oil. Extensive remaining proven reserves as well as decreasing processing costs has resulted in growing interest in natural gas since last decades. However, the use of natural gas comes with an inherent limitation due to its gaseous form, its storage and transportation cost. The development of liquefied natural gas (LNG) processes provides a cost-effective substitute to pipeline and compressed natural gas transportation, which have reached their limits in such a global trend. In fact, the volume of LNG is minute (1/610) (Kidnay, et al., 2011) compared to the corresponding volume of natural gas at atmospheric pressure. Therefore, the demand for LNG has increased substantially as a viable replacement to pipelines for natural gas transmission.

LNG is produced by chilling natural gas to approximately -162 °C (-259 °F) at normal pressure, thereby condensing the gas into liquid form. Due to its reduced volume, LNG offers an efficient logistic solution for delivery of natural gas. LNG is typically transported by specialized tankers with insulated walls and is retained in liquid form by autorefrigeration, a process that keeps the fluid at its boiling point. Despite that, the fluid vapours caused by any heat additions, known as Boil-off Gas (BOG), are discharged from the storage to power the vessel.

Generally, the LNG supply chain consists of natural gas production, its liquefaction into LNG, transportation of this fluid to world markets commonly through ships, the regasification or re-vaporization of LNG back to its gaseous form, and finally dispatching this gas to customers by normal pipeline. The process is shown in Figure 1.1-0 as block flow diagram.

Primarily, natural gas is mixture of methane and several constituents, including ethane, propane, heavier hydrocarbons, nitrogen, carbon dioxide, sulphur, and other inert components. Depending on the quantity of its components, natural gas possesses physical and chemical properties, such as methane number, calorific value, Wobbe index, density, dew point, and others. Altogether these components (their percentage contribution) and properties (represented by numerical values) constitute the "specifications" or "quality" (or quality parameters) of a particular natural gas blend.

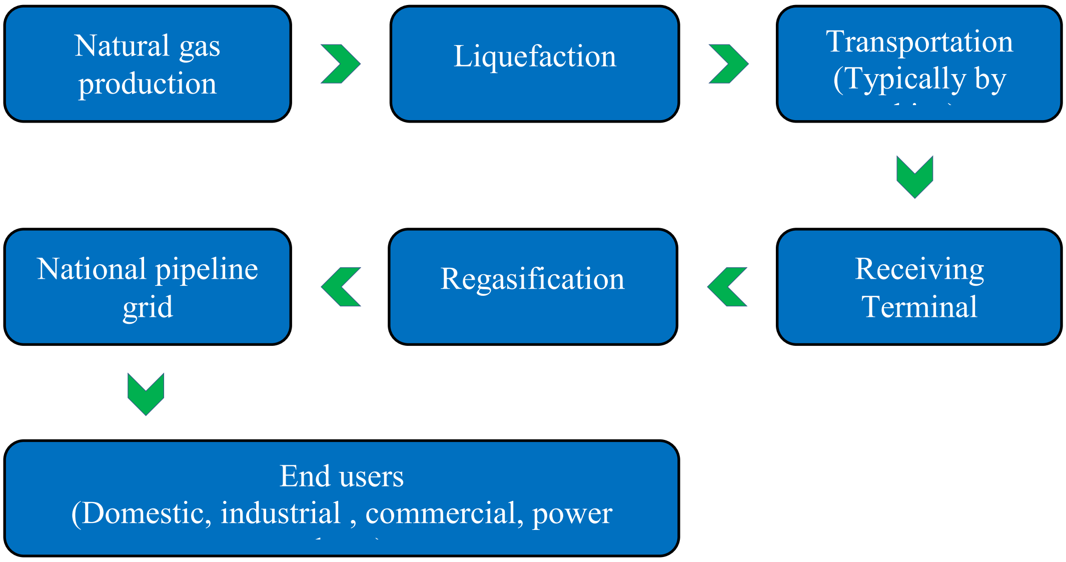

Figure 1.1-0: Typical LNG supply chain

The quality of natural gas greatly affects its end-use performance (e.g., burner efficiency in combustion use, or industrial yield in chemical synthesis when used as feed-stock). These specifications have certain purposes, including corrosion prevention, avoiding condensation in pipelines and performance of combustion systems. Quality of natural gas depends on nature of the origin/ underground formation (or the nature of biomass in case of biogas), called as "reservoir" or "source", from which it is tapped by means of drilling. Therefore, LNG produced by plants at different locations (with their specific natural gas sources) considerably varies in terms of its quality. Presently, Qatar is the largest LNG exporter with a volume of 77.4 MTPA of 71.84 Methane Number, while Malaysia occupies the second place with 23.1 MTPA LNG of Methane Number 70.54 (International Gas Union (IGU), 2013).

1.1 Finnish LNG Market and Challenges

With an annual consumption of 35 TWh (Finnish Gas Association, 2013), Finland has a mature natural gas market since 1973. Because of broad applicability, LNG holds enormous potential in the Finnish energy system. Currently, Finland has a small-scale LNG setup; the state natural gas operator, Gasum, owns a production plant in the Kilpilahti industrial area in Porvoo. Established in 1996, it produces around 20000 tonnes of LNG a year (Gasum Oy., 2013).

In contrast to other countries, Finnish natural gas market is chiefly based on electricity and heat production besides industrial usage. The share of natural gas in the country's Total Primary Energy Supply (TPES) steadily increased from 3% in 1977 to 10% in 2011; Figure 1.1-1 statistically illustrates the exact trend (International Energy Agency, 2012) (OECD/IEA, 2013).

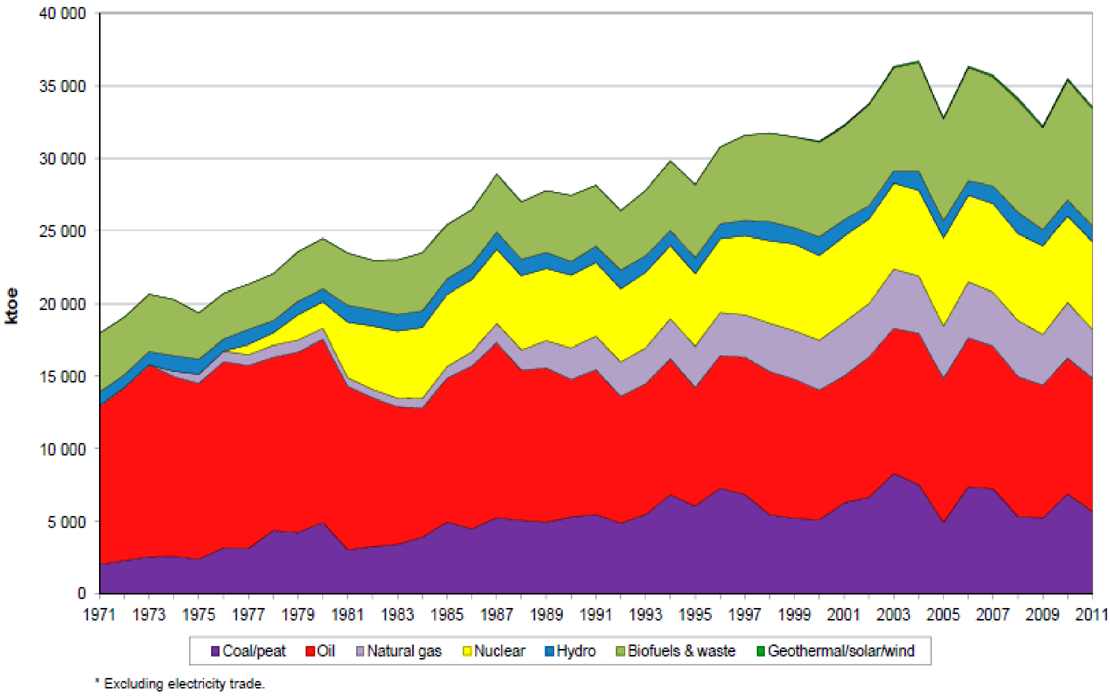

Figure 1.1-1 (OECD/IEA, 2013): Total Primary Energy Supply (TPES) in Finland

In 2012, the transformation sector (CHP) remained the largest consumer of natural gas in Finland, as depicted by Figure 1.1-2, representing about 57% of the country's total gas consumption, while industrial use and district heating claimed 27.9% and 12.4% respectively. Overall, the natural gas was utilized mainly for industrial processes (41.5%) and secondly for space heating and hot water production (35.1%)

in which household and commercial usage represented only 2.3% (Finnish Gas Association, 2012) as shown below in Figure 1.1-2. Analytically, 25 power plants accounted for 43.3% of the total natural gas consumption, followed by heavy industry (41.6%) and district heating plants (12.4%) (Finnish Gas Association, 2013) as explained in Figure 1.1-3.

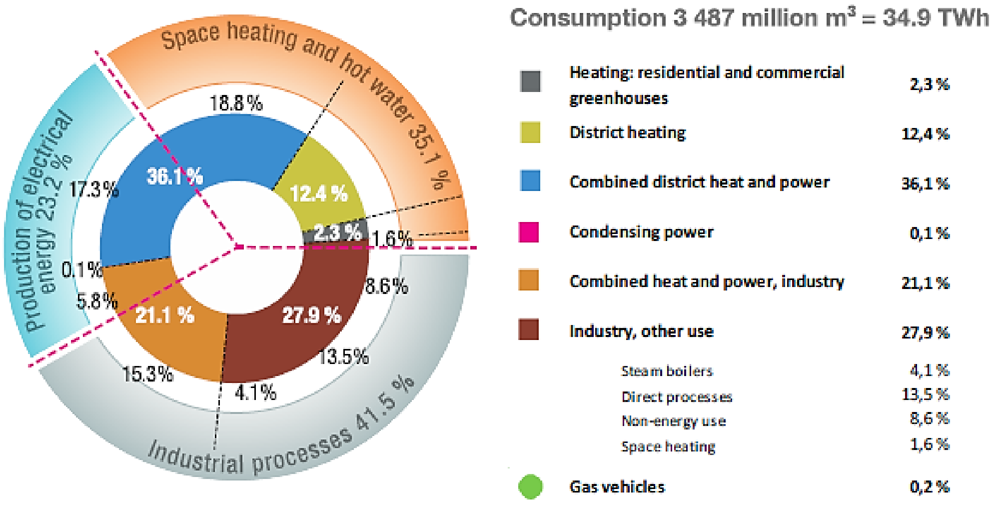

Figure 1.1-2 (Finnish Gas Association, 2013): Natural gas consumption in Finland 2012

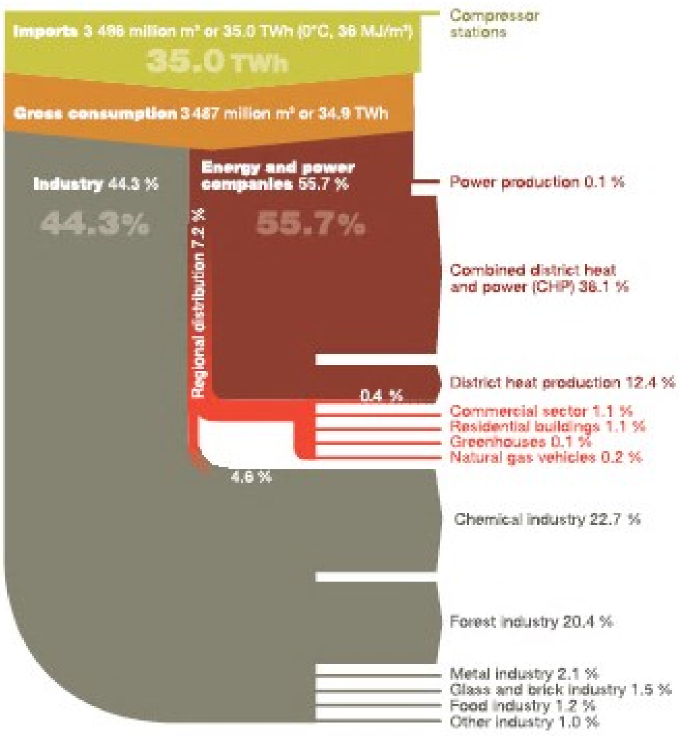

Figure 1.1-3 (Finnish Gas Association, 2013): Natural gas consumption by market sectors in Finland 2012

Based on these statistics, the following have been identified as the major utilization areas of natural gas (potential LNG market segments) in Finland:

a) engine applications in marine and on-shore (land) traffic
b) off-grid industrial consumers
c) users of the current national gas grid

1.1.1 Drivers

LNG currently assumes a major importance in the Finnish national energy mix. The LNG market is presently gaining substantial attention; the key drivers underlying this growing prominence in the above three sectors include a considerable amount of local and international legislation, liberalization of the natural gas market, energy security due to full reliance on Russian supplies (Energy Market Authority, Finland, 2012), and the traffic infrastructure.

This legislation, mainly implemented by the EU (European Union) and the IMO (International Maritime Organization), fundamentally applies stringent control measures on environmental pollutants, such as sulphur, NOx (for Tier III), total hydrocarbons, particulate and CO, which can be achieved if LNG is used as a marine fuel in place of currently in practice HFO (Heavy Fuel Oil) and MDO (Marine Diesel Oil).

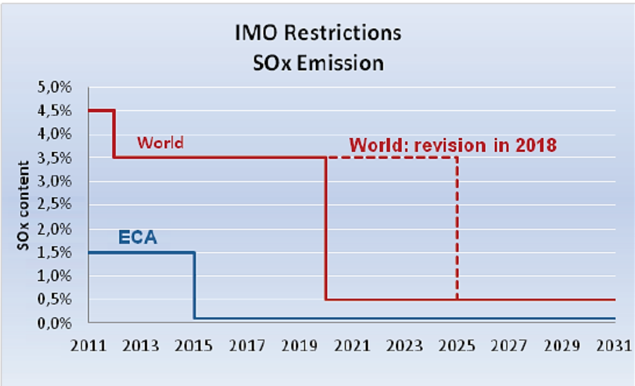

Figure 1.1-4 (Semolinos, et al., 2013): IMO regulation for SOx emission

Figure 1.1-4 and Figure 1.1-5 show the IMO allowable sulphur and NOx limits with implementation dates for emission control areas (ECA), according to which, SOx emission are required to be reduced from 1.5% to 0.1% by member countries by 2015. Since located along Baltic Sea ECA (Figure 1.1-6), Finland is bound to employ these measures particularly for sea transport.

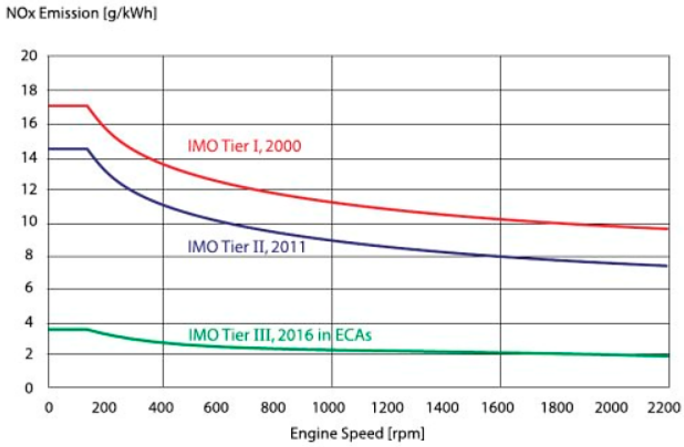

Figure 1.1-5 (Hyundai Engine & Machinery Div., 2012): IMO MARPOL Annex-VI NOx Emission Limits

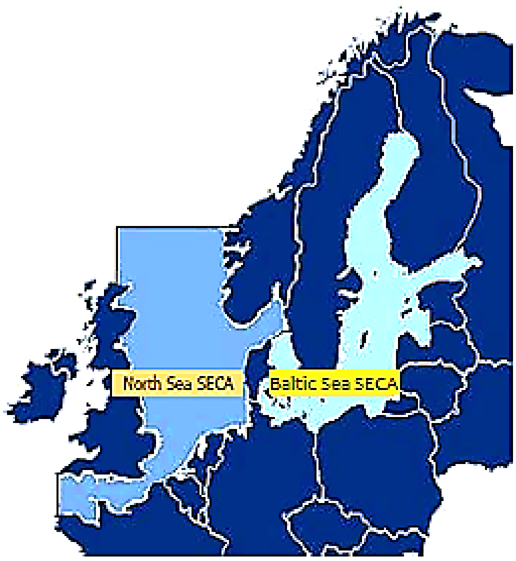

Figure 1.1-6 (Gasum Oy., 2013): Designated Sulphur Emission Controlled Area (SECA)

Other statutory drivers include the following:

- EU's Clean Fuel Strategy (European Commission , 2013)
- directives COM(2013)17 *European alternative fuels strategy* (European Parliament, Council, 2013) and COM(2013)18 *Directive on the deployment of alternative fuels infrastructure* (European Parliament, Council, 2013)
- Commission Directive 2012/32/EU regarding sulphur content of marine fuel in line with IMO MARPOL Annex VI (European Commission, 2012)
- IMO's marine pollution (MARPOL) convention Annex. VI (International Maritime Organization (IMO), 2013)
- Regulation (EC) No. 715/2007 of the European Parliament on transition from Euro 5 norm to Euro 6 norm for road transport (European Union, 2013)

- EU's Industrial Emissions Directive (IED) 2010/75/EU (European Parliament, Council, 2010)
- Finnish environmental protection act PINO for industry/ power plants (Finnish Ministry of Environment, 2011)
- Liberalization of natural gas market as per Natural Gas Market Act §508/2000 (Finnish Ministry of Employment and the Economy , 2013)

Additionally, the access and connection to European natural gas grid, and energy security instead of full reliance on Russian supplies constitute the strategical aspects towards and LNG market for Finland.

In view of these factors, LNG offers a solution in order to economically cope with environmental requirements. As a marine fuel, LNG decreases greenhouse gas

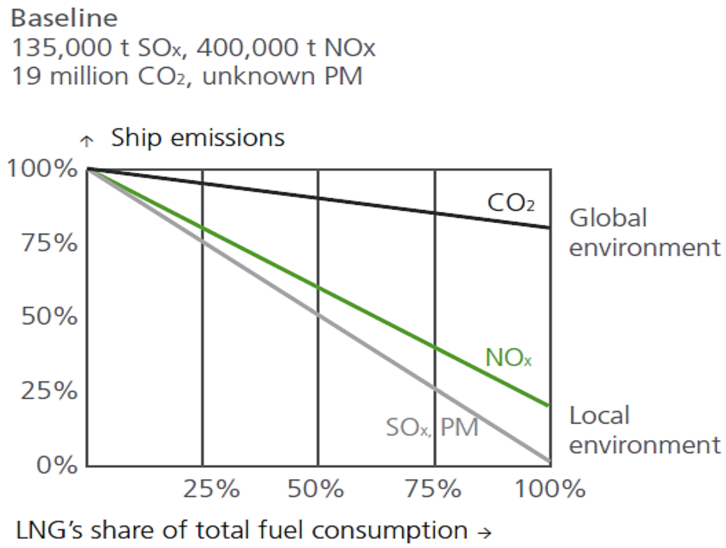

Figure 1.1-7 (Det Norske Veritas AS (DNV), 2010): Contribution of LNG to mitigate ship emissions

emissions as shown in Figure 1.1-7 illustrating LNG's potential as an environmentally friendly fuel in shipping.

1.2 Thesis Motivation and Research Goals

Previously, the LNG buyers had some flexibility in ranges of natural gas properties acceptable to them, as they commonly used this LNG for power production only. However, the situation changes currently as LNG trade becomes more global. New markets have emerged where pipelines to consumers already exist and the consumers have specifications which are outside the range of the LNG produced at many locations. This situation poses gas interchangeability, compatibility or harmonization challenges, assigning a key importance to LNG quality specifications in the LNG industry (Coyle, et al., 2007).

Although LNG trade is widespread with a variety of specifications depending on the production source location and type of reservoir (Egging, et al., 2008), little effort has been dedicated to set standard specifications for LNG on global or local levels. The same holds true for Finland which is not connected to the European natural gas grid. Finnish gas grid consists of 1310 km transmission pipeline and is wholly dependent on Russian natural gas, as shown in Figure 1.2-1 below. This is one reason for little consideration to Finnish market by a number of European initiatives aimed at harmonizing the natural gas (including vapourised LNG) specifications and business.

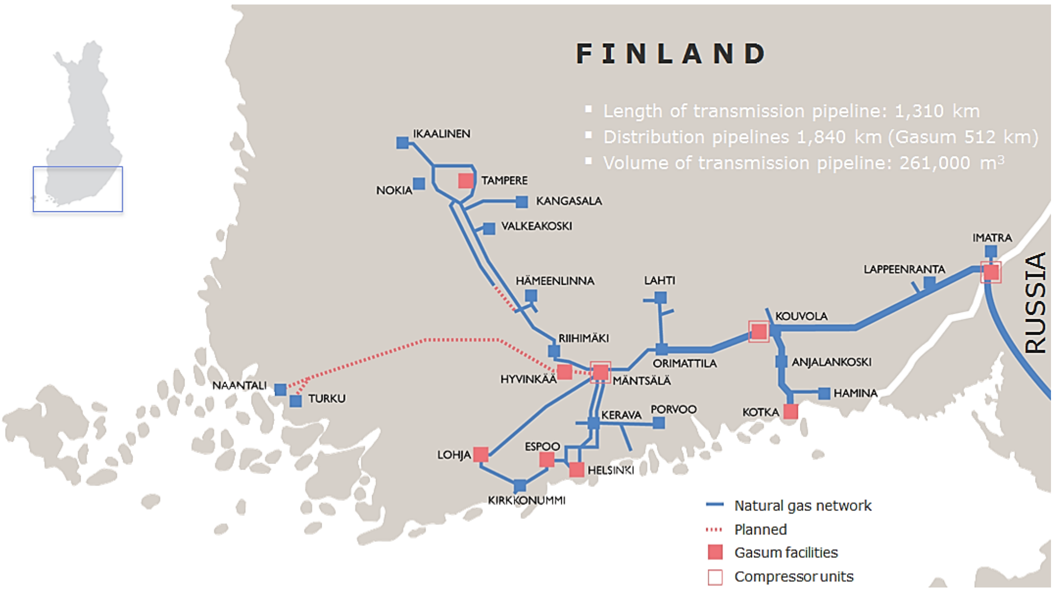

Figure 1.2-1 (Gasum Oy., 2012): Finland's natural gas pipeline grid owned by Gasum Oy

These studies are conducted under the banner of EASEE-gas (The European Association for the Streamlining of Energy Exchange) and CEN (Comité Européen de Normalisation – the European Committee for Standardization), which have the support of the European Commission (Williams, 2009). Furthermore, preliminary efforts in this direction have been made in the US (Coyle, et al., 2007) and the UK, which resulted in standardizing the acceptable LNG qualities imported from various origins. However, there is no European natural gas automotive market fuel specification, while diesel (EN 590), gasoline (EN 228), and even LPG (EN 589) already have their own specifications (The Advanced Motor Fuels Implementing Agreement (AMF), 2012).

Prompted mainly by the environmental movement, Finland has to build an LNG infrastructure by constructing terminals along its coast, yet with an established natural gas market and a pipeline network, it must develop quality specifications of LNG beforehand, conforming to its market requirement, in order to determine which LNG quality is to import. Current Finnish supply is based on Siberian gas which consists of 98% methane content; hence all LNG qualities may not generally suit the market. Moreover, the liberalization of Finnish gas market (by interconnection with European gas grid) is bound to raise gas harmonization issue in near future. Hence, it is important to set up natural gas standard specifications making it possible to import only the desired quality LNG which is compatible (or at least the closest) to the existing natural gas usage in the country. This thesis establishes the LNG quality parameters in accordance with the natural gas market demand in Finland. Furthermore, this body of work describes the design of an upgradation facility in order to modify the property profile of LNG imported into the country.

Primarily, the thesis aims to address the following three questions:

1. **What quality of LNG would jointly (or individually) fulfill the requirements of the following three applications in Finland?**
    - **engine applications in marine and onshore/land traffic**
    - **off-grid industrial consumers**
    - **users of the current national gas grid**
2. **Which are the best-fit LNG sources available internationally?**
3. **How can the LNG of desired quality be produced (a basic model)?**

1.3 Scope

The study encompasses determination of natural gas type required in Finnish market. This thesis achieves the objective by examining the natural gas requirement of the three selected applications in Finland, the physical and chemical attributes of the imported LNG, as well as an optimal technique for quality modification of LNG in the form of simulated model. The preferred specifications of natural gas/ LNG is finally suggested which is suitable to all three applications of natural gas in the region These pertinent characteristics of natural gas are evaluated through comparison of the required and available specifications. Influence of various parameters on acceptability of LNG sources was determined by means of sensitivity analysis.

1.4 Research Methods and Tools

Contemporary research procedures, such as archival study, correlational research and computer simulation, were employed to accomplish the research targets. Since, the study is principally directed to develop the quality standards of the LNG interchangeable with the existing natural gas for various applications in Finland, the research work commenced by examining the consumer requirements of the market under consideration, followed by measurement of the LNG properties imported from different sources. These results defined the operating variables of the LNG after vapourization as the gas-mix. Subsequently, the design of the upgrading system was proposed and modeled in order to adapt the fuel to the demands of the Finnish market.

The gas quality specifications, especially the methane content, were studied by harvesting the data available from Gasum. This data comprised the pipeline gas specifications and properties with details of impurities and other quality parameters. Furthermore, gas quality requirements for the selected applications were explored through literature review and enquiry from manufacturers in order to search the LNG quality available in the world.

Additionally, software tools GasCalc *version 2.3.2* by ©E.ON Ruhrgas AG, and Aspen HYSYS v8.0 process simulator were respectively utilized to calculate methane number of the available blends and to construct a model for the LNG quality adjustment system.

Assistance was also sought from Gasum's intranet "gasnetti", online gas quality measurement system (at custody transfer point Imatra), online monitoring/SCADA system, and gas dispatching data at Kouvola. To collect the information, visits were conducted to Kouvola and LNG production plant at Porvoo.

The standard operating procedures (SOPs) and guidelines of the local natural gas regulator, the Finnish Gas Association, and the Energy Market Authority complemented the study.

The market requirements and available LNG specifications were compared, and compatible LNG qualities were found. A model was also constructed to upgrade the deviant LNG to suite the market demand.

1.5 Thesis Outline

The thesis is composed of six chapters. Chapter 1 gives a brief introduction to the topic and defines the research objectives. With literature background, Chapter 2 concisely overviews the previous research in the field while focusing on the LNG supply chain and LNG quality modification. Chapter 3 introduces the detailed characteristic data of the designated natural gas sectors required by Finnish market and the LNG specifications available worldwide. This data is compared in Chapter 4, thereby defining a framework of suitable LNG sources for Finland based on actual demand windows. Chapter 5 describes the quality modification of incoming LNG to adapt Finnish grid in terms of a model process selected by comparison of simulations for 3 alternative processes, built on Aspen HYSYS simulator environment. Finally, Chapter 6 discusses the results and concludes by stating significance and implications of research findings presenting recommendations for possible directions of further research on this topic.

2. Theoretical Perspective

In order to address the key research question, a brief outlook of the LNG industry holds paramount importance. This chapter is focused on the background of LNG value chain, the quality of natural gas and its interchangeability with short description of methods to adjust the quality of LNG.

2.1 LNG Supply Chain

LNG is primarily the natural gas in liquid form; it has all physical and chemical properties and utilization similar to natural gas i.e., odorless, colorless, non-corrosive, non-toxic, yet natural gas vaporized from LNG may cause asphyxiation in an unventilated confined space. Practically, natural gas was first converted to liquid phase by the United States Bureau of Mines in 1917 as a by-product, since the main purpose was to extract helium from natural gas, in order to use in air ships (Peebles, 1992). In fact, 0.035 m^3 (1ft^3) of pure methane in liquid form at 111 K (-260 °F) equals about 18 m^3 (630 ft^3) of gaseous methane (Podolski, et al., 2007). This remarkable yield characteristic of LNG (which is mostly methane) facilitates its overseas transportation by ships, local distribution by trucks, and storage opportunities, thereby making it attractive as a preferred fuel for economic reasons, and a flexible fuel available throughout the world on a wide perspective.

In broad terms, LNG supply chain encompasses every activity and the equipment to carry the LNG from well-head to the burner-tip. Figure 2.1-1 imparts a general idea of LNG supply chain.

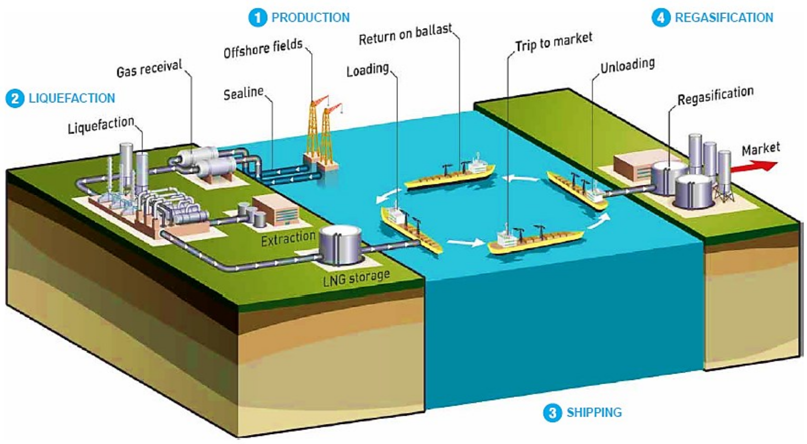

Figure 2.1-1 (TOTAL S.A., 2012): Typical value chain of LNG

This chain is generally long and expensive due to remote destinations and capital costs involved in facility and paraphernalia. Typical components of the chain include the following:

1. Production-well infrastructure of natural gas in oil/gas field
2. Oil/gas field processing of gas, if necessary
3. Gathering-system (pipelines) from well to the gas processing/ conditioning plant
4. Refrigeration plant for feed gas liquefaction (LNG)
5. Storage and loading arrangements to ship the LNG
6. Transportation through marine vessels or trucks
7. LNG import/ receiving terminal, including LNG storage tanks, regasification or vapourization, quality adjustment facility, and gas sendout compression
8. Injection to the grid through gas transmission pipeline, or distribution network, or gas delivery to distant, small off-grid customers by truck

Ships and vehicles using LNG as liquid fuel becomes an emerging element of LNG chain. Therefore, the supply chain may largely be extended to include intermediate/redistribution LNG terminals, vehicles, gas-fuelled vessels, LNG refueling stations and bunkering solutions. Four (4) main stages of the chain are briefly described here.

2.1.1 Production

LNG is produced in a fashion similar to conventional natural gas production procedures. Depending on the gas-source, natural gas is normally subjected to the purification process to remove variety of impurities such as water, CO_2, CO, hydrogen, Hg, nitrogen, oxygen, sulphur and higher hydrocarbons. Natural gas production flow is described in Figure 2.1-2. The process involves no chemical change during purification. The type and amount of the impurities solely depend on the source; different gas sources tend to possess different gas compositions.

There are three basic types of LNG processing facilities:

- Base-load plants (for constant and steady supply of LNG to customers)

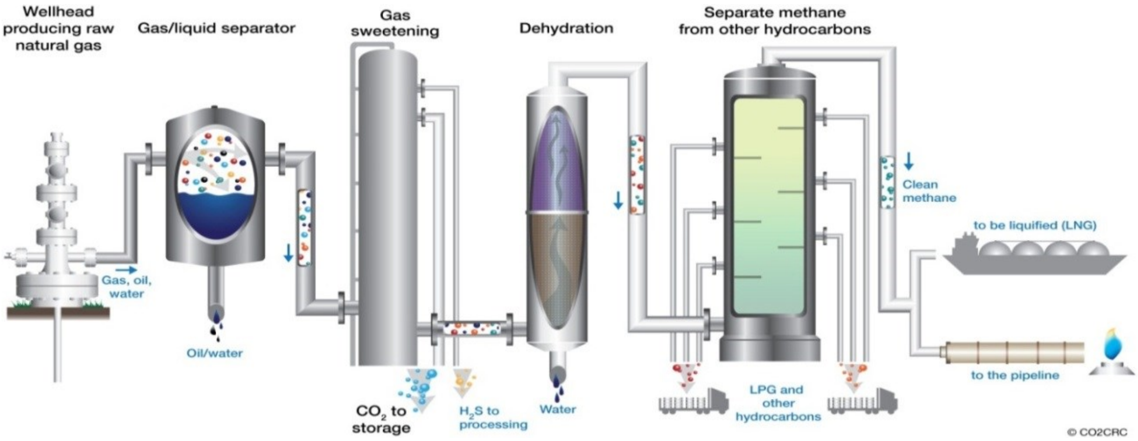

Figure 2.1-2 (CO2CRC, 2011): Natural gas production

- Peak-shaving liquefaction & storage (liquefy and store LNG in summers for eventual regasification in winter peak loads, by definition, smaller than base-load plants) Typically, small-scale LNG technologies, such as nitrogen turbo-expanders, are used for peak-shaving (Economides & Wood, 2009).
- Satellite LNG stations (do not contain liquefaction, but only storage and re-gasification equipment; they supply gas, through trucks, to the remote, small localities, or for vehicle fuels)

2.1.2 Liquefaction

Natural gas selected for the liquefaction is metered and pressure regulated to match the plant operating pressure. As shown in Figure 2.1-3, it is first subjected to contaminant treatment and the separation of heavier hydrocarbons in order to prevent their freezing in the main cryogenic heat exchanger (MCHE). Subsequently, the gas is liquefied using high level and low level refrigerant; it is further cooled in the cryogenic section to approximately -160 °C to -165 °C (depending upon the composition of the feed gas), to a total liquid, the LNG. This mildly pressurized LNG is then subcooled in one or more stages to facilitate storage at pressures slightly above atmospheric. Flashed vapours and boil-offs are recycled within the process. Liquefaction is carried out by a refrigeration cycle, in which a refrigerant chills the natural gas by consecutive expansion and compression. In a typical LNG plant, natural gas is treated and liquefied in numerous parallel refrigeration units known as "trains", and is then sent to the storage tanks. Generally, liquefaction is part of natural gas production facility.

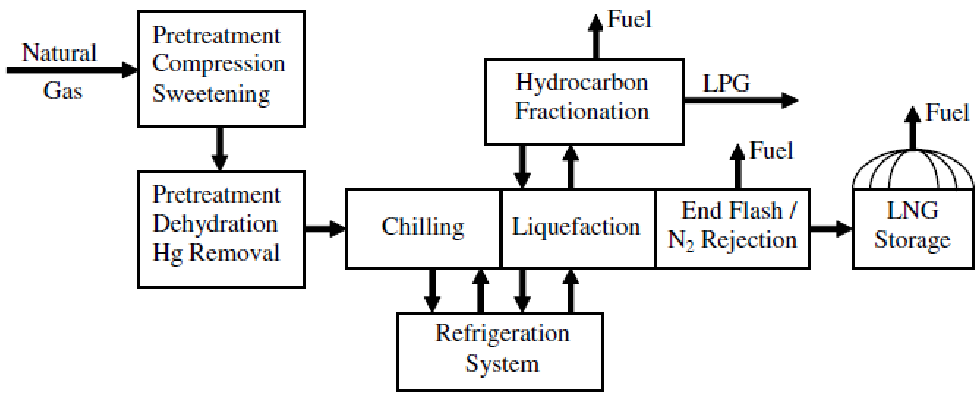

Figure 2.1-3 (Barclay, 2005): Typical LNG plant block flow diagram

The basic motive of liquefaction cycle is the removal of the sensible and latent heat of natural gas. This process would be as efficient as it is closer to the natural gas cooling curve (as indicated in Figure 2.1-4). The fundamental principle of a refrigeration cycle comprises:

- Cooling and condensation
- Expansion and flashing
- Evaporation
- Compression

The efficiency of Joule-Thomson gas liquefaction cycle can be measured by the ratio of refrigeration produced by mechanical work. In comparison to the Carnot efficiency, this ratio improves with lower temperature differences. (Adorjan, 1991)

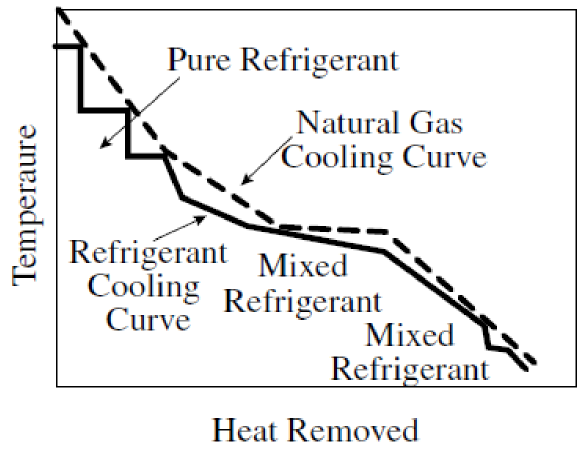

Figure 2.1-4 (Wang & Economides, 2009): Natural gas/refrigerant cooling curves

Two most important liquefaction cycles are:

- Cascade cycle
- Mixed-refrigerant cycle

In the cascade plant, the liquefaction process is performed with various refrigerants (e.g., butane, propane, ethane, methane, or nitrogen, or mixtures of them). Depending on the number of stages used in the cascade, the plant might be expensive due to numerous compressors, heat exchangers, storage tanks. But it could be simplified by using a single refrigerant which can be a mixture of any of the above.

In mixed-refrigerant cycle, the working fluid is expanded at different pressure levels, and the liquid and gas are separated after each expansion. The gas is then compressed, and the liquid is passed on to next stage, thereby eliminating the recompression of full amount of working fluid, which results in higher efficiency. In general, natural gas is feed or process fluid while any refrigerant could be working fluid. If the process fluid itself is the working fluid, it is known as "open cycle", otherwise a "closed cycle".

Though the overall thermal efficiencies of both these cycles are comparable, yet mixed-refrigerant cycles are more popular due to lower initial investment (Tusiani & Shearer, 2007). The operation of this type of cycle, however, necessitates the blending and control of the refrigerant mixtures.

Several proprietary processes are marketed on the basis of above cycles, for large-scale baseload natural gas liquefaction plants. These processes fall into the following general categories (Tusiani & Shearer, 2007):

a. Pure-refrigerant cascade process

Three discrete pure component refrigerant cycles are used in this process at three cooling steps (-32 °C, -96°C, -163°C) each one of them consists of a compressor, a condenser, an expansion/ throttling valve and an evaporator. The refrigerants used in sequence of the cycles are propane, ethylene and methane. The process is simple (schematic diagram is given in Figure 2.1-5) and easy to control, but has lower thermal efficiencies, which increase its cost.

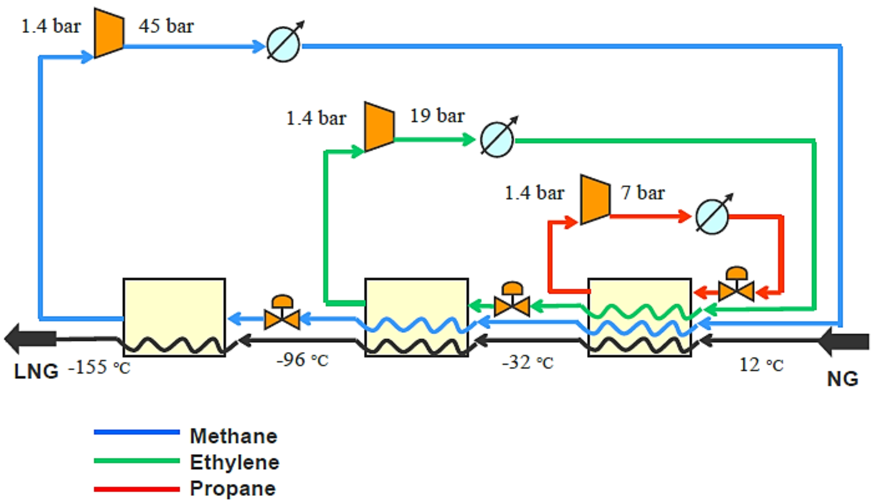

Figure 2.1-5: Schematic diagram of Cascade Process

b. Propane-precooled mixed-refrigerant processes (C3-MR Cycle)

This process is used in more than 80% of the LNG liquefaction processes (Tusiani & Shearer, 2007). The system uses multi-component refrigerant (commonly nitrogen, methane, ethane, butane, and pentane) to condense and evaporate natural gas in one cycle over broad temperature range. Notable Multi-Component Refrigerant (MCR) is Air Products & Chemicals Inc.'s (APCI) proprietary. The precooled feed gas is sent to main cryogenic heat exchanger (MCHE), where it is condensed and subcooled at raised pressures. The APCI MCHE has thousands of small-diameter spiral-wound tubes over the length of whole heat exchanger (displayed in Figure 2.1-7), through which natural gas and MCR flow upward for condensation and cooling. The cycle is highly efficient. General diagram is shown in Figure 2.1-6.

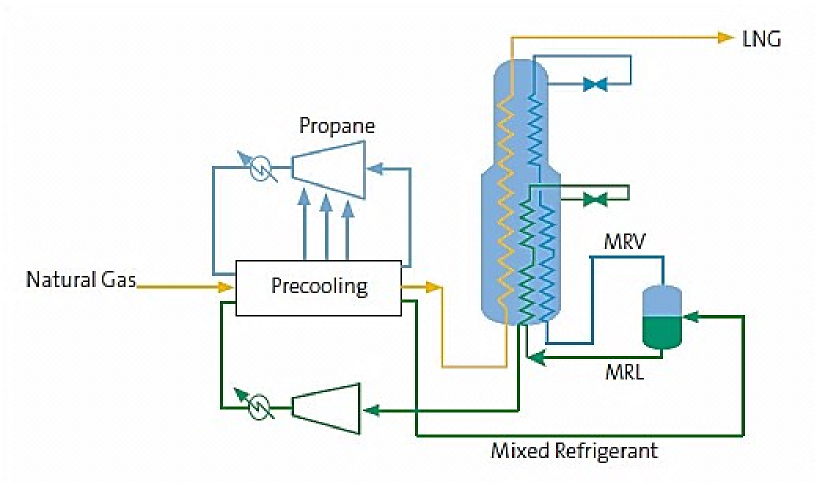

Figure 2.1-6 (Air Products and Chemicals, Inc., 2013): Air Products Propane-precooled mixed-refrigerant (C3-MR) process

c. Other mixed-refrigerant processes

A little variant of the C3-MR cycle, these include Shell dual mixed-refrigerant (DMR) process, Axens Liquefin DMR process, Statoil-Linde mixed fluid cascade (MFC) for example. They utilize different combinations of refrigerants and variety of heat exchanger equipment (for instance, coil-wound heat exchanger as shown below in Figure 2.1-7) to enhance efficiency, reduce cost, increase vendor competition, and reduce carbon footprints.

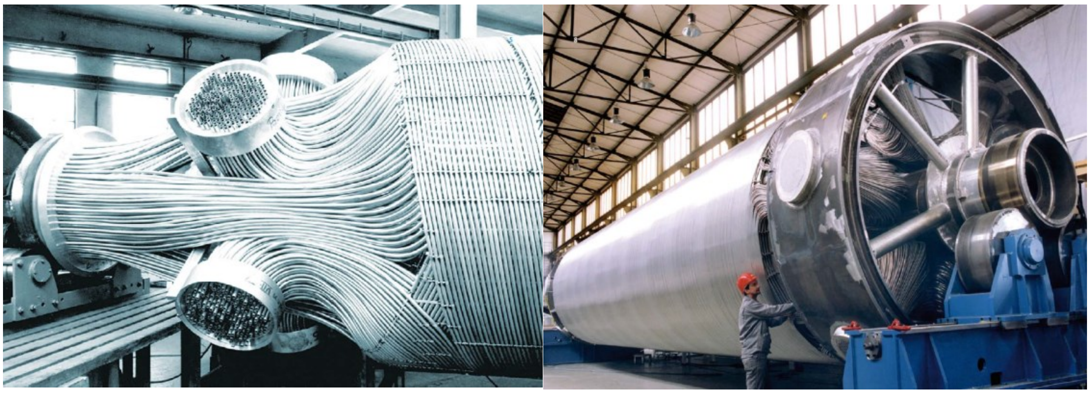

Figure 2.1-7 (Linde AG, 2012): Tube arrangement of a Coil Wound Heat Exchanger (CWHE)

d. Nitrogen expander-based processes

High-pressure nitrogen vapor from a nitrogen compressor is cooled against water and is then further cooled and expanded in a series of expanders and heat exchangers to provide refrigerant flow at the required temperatures and pressures. After cooling and liquefying the natural gas flow, the low-pressure nitrogen is partially compressed using energy from the expanders, reducing the power required in order to return the circulating gas to high pressure in the main nitrogen compressor. These are ordinarily used in small baseload, offshore, and peak-shaving applications owing to their simple, robust, and compact designs. Example is APCI's AP-X process.

2.1.2.1 Gasum LNG plant, Porvoo

Figure 2.1-8 exhibits the small-scale and the only LNG production plant in Finland located at Porvoo, owned and operated by Gasum Oy.

Figure 2.1-8 (Gasum Oy., 2013): Gasum's LNG production plant at Porvoo

With a capacity of 20000 tonnes per annum, this plant uses LIN (liquid nitrogen) as refrigerant which is delivered at battery limits to the LNG plant at 12 barg and -193°C. A cascade of heat-exchangers cool the pre-treated clean, dry feed gas up to -138°C, which then travels downwards in the liquefier (Figure 2.1-9) in tube-side of a coil-wound heat-exchanger (CWHE) and is condensed, subcooled into LNG due to contact with LIN in shell-side. LIN is vented to atmosphere as gas. (Hamworthy Gas Systems AS, 2010).

Figure 2.1-9 (Gasum Oy., 2013): Gasum's NG liquefaction unit/ liquefier at Porvoo

The world total liquefaction capacity remained 280.9 MTPA by end 2012 with Qatar leading all the way, followed by Indonesia and Malaysia (International Gas Union (IGU), 2013) as illustrated by pie graph in Figure 2.1-10.

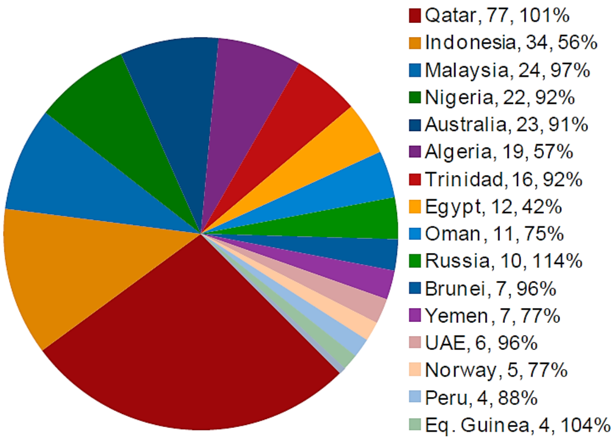

Figure 2.1-10 (International Gas Union (IGU), 2013): Liquefaction Capacity by Country (2012), Capacity (MTPA) and Utilization

2.1.3 Storage

LNG storage is essential part of liquefaction as well as regasification facility, where LNG is stored for the time until it is loaded for shipment or re-vapourized for pipeline injection and end-users.

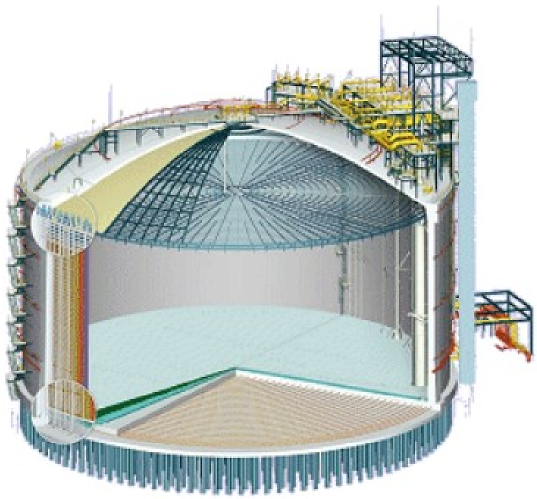

Figure 2.1-11 (LUSAS, 2013): A 3D model of 200,000m^3 above- ground tank for the KOGAS-Tech Pyeongtaek facility, South Korea

Storage, the second major expense in the LNG-chain, can be above-ground or in-ground tanks used for load-balancing (continuously) or peak shaving modes. A rendering of an above-ground LNG storage tank is depicted in Figure 2.1-11. Their major purpose is to keep the cryogenic LNG in liquid form at a temperature not higher than -163°C (Tusiani & Shearer, 2007), which makes them capital intensive due to special construction materials (e.g., Nickel steel) and design. LNG technology has matured during the past 60-70 years, and historically, many materials, similar to those in cryogenics, has been in use. Structural materials include metals (304L stainless steel, 9%-Ni steel, aluminium, copper) and concrete, while insulating materials are perlite, polyurethane foam, fiberglass, mineral wool, cellular glass, perlite concrete, evacuated insulation, PVC foam, epoxy-impregnated hardwood, densified wood laminate, calcium silicate and even perlite-filled plywood boxes, and balsa wood (Adorjan, 1991). These materials are then coated with different adhesives and mastics for water-proofing. The storage tanks are divided into three types (Mokhatab, et al., 2014) for onshore terminals:

- Single containment tank
- Double containment tank
- Full containment tank

Tank failure may be caused by phenomenon of "rollover", which is the speedy intermixing of two or more separate layers of dissimilar concentrations. This is due to stratification (i.e., formation of layers) of two unmixed cryogenic liquids of different densities, or to auto-stratification with preferential release of light components e.g., nitrogen and methane. When a tank already having some LNG is filled further with a shipment of variant quality (density), the two liquids may remain unmixed creating independent layers. The densities of two LNG layers tend to equalize accompanied by weathering and heat absorption, thereby changing the temperature of the whole mixed LNG. At these conditions, if the mixed LNG is superheated corresponding to the vapour pressure in the tank, the vapourization rate rises abruptly. This may activate the emergency relief vent system and is hazardous to the tank structure if the vapour flow rate beats the system capacity. Stratification and auto-stratification can be avoided if separate tank is used for each variety of LNG density, or the proper mixing (e.g., jet nozzles, filling with multi-orifice tube, alternate filling at top and bottom) is carried out during the filling operation, and by keeping the nitrogen fraction of LNG to lowest ebb.

2.1.4 Transportation

Once liquefied, LNG is transported from liquefaction plant to regasification plant and end-use market by LNG tanker ships or through rail, road (tucks) or barges for local distribution.

2.1.4.1 LNG Shipping

The global LNG ship fleet has been growing rapidly in the last 10 years, and as illustrated in Figure 2.1-12, there are presently (end 2012) more than 378 operating tankers around the world, which include 14 FSRUs and 14 ships of less than 18000 m^3 (International gruop of liquefied natural gas importers (GIIGNL), 2012).

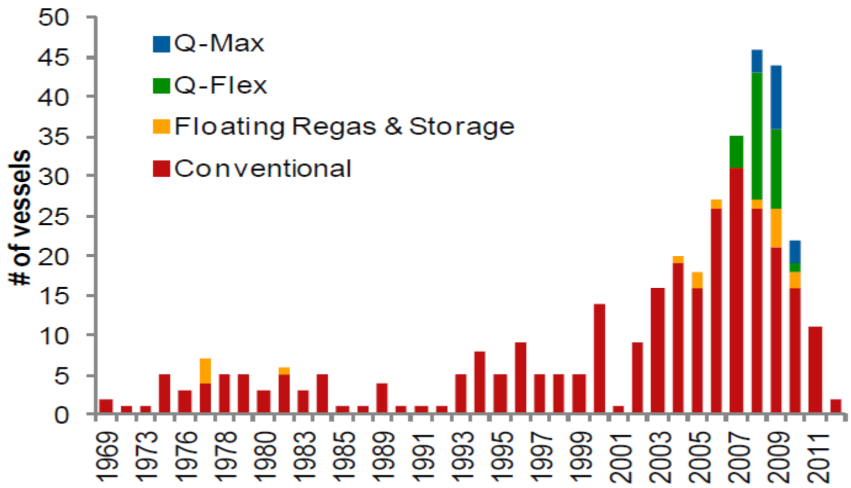

Figure 2.1-12 (International Gas Union (IGU), 2013): Evolution of LNG tankers fleet by year of delivery 1969-2012

LNG remains in liquid phase during transportation by high level insulation of the LNG tanks in a ship only, not by cooling or compression. As a result of non-ideal insulation, roughly 0.10-0.25% of the LNG boils off daily though, it remains a safer cargo for the marine vessels. For over 40 year history, there are no reports for any shipboard fatality, or cargo fire in spite of eight LNG-spill incidents and seven other non-spill occurrences which caused minor ship damages due to collision and grounding (Bubbico, et al., 2009).

There are traditionally two basic different designs for LNG ships: freestanding tanks [spherical (Moss), and prismatic] and membrane hull design ships (including the latest Q-Flex and Q-Max). Both designs traditionally burn the boil-off along with conventional heavy oil and use the energy in steam turbines in order to run the cargo. The following pictures in Figure 2.1-13 and Figure 2.1-14 show the typical designs of Moss-type and Membrane-type LNG carriers.

Figure 2.1-13 (Moss Maritime a.s, 2009): Typical Moss-design LNG tanker (LNG Sokoto)

The two technologies are rather evenly split between the two designs, even though the membrane design has been preferred in recent years, as it allows on-board re-liquefaction on the LNG. In that case the ship is mostly powered by diesel engines which have up to 30-40% better overall efficiency than conventional steam turbines. The re-liquefaction process includes compression and condensation of the boil-off gas, while refrigeration of the system is provided by a nitrogen Brayton cycle. (Mokhatab, et al., 2014)

Figure 2.1-14 (GlobalSecurity.org, 2011): Typical membrane-design LNG tanker

As the transportation cost of LNG is critical in the economic viability of a LNG project, the size of the vessels has also been improved. The average capacity of a conventional LNG carrier is about 140000 cubic meters, whereas newest built Q-Flex and Q-Max cargoes can carry up to 260000 cubic meters of LNG. (Tusiani & Shearer, 2007)

2.1.4.2 LNG Trucking

Since the LNG pipelines are considered uneconomical and technically challenging (due to BOG issue in the pipeline), "trucking" is another method to transport LNG in lesser volumes in the cases:

- if regasification plants are at small distance from the liquefaction facility
- supply to off-grid customers
- supply to a satellite LNG facility
- supply to an LNG re-fueling station.

Special-material, double-walled heavy-duty tanker trucks deliver the LNG to destination effectively. LNG trucking is in service since 1968 with a tanker capacity 6-20 tonnes (CE, Class 8) (International Group of Liquefied Natural Gas Importers (GIIGNL), 2009).

Figure 2.1-15 (Heidi, 2009): A Gasum 50 m^3 LNG transport truck; Gasum has 4 such double skin vacuum insulated tanker-trucks.

These trucks carry LNG volumes as much as 40 to 80 m^3 (The Danish Maritime Authority, 2012) up to an optimal distance of 600 km and could also be in the form of trailer, semi-trailer or articulated lorry. Furthermore, standard 40-foot ISO containers have also been experimented by fitting them to trucks, trailers, to be transported through rail and container vessels (CNSS, 2013). The container solution is newer to the LNG logistic chain. Figure 2.1-15 shows one of Gasum's LNG trucks plying on the road. If consumers are at long distance from LNG import terminal, that is uneconomical for trucks, then smaller intermediary terminals are built as large as

100000 m^3 capacity. Small- and medium-scale LNG carriers (vessels/ barges) are used in this case. They are either “bunker vessels” or “feeder vessels”. The former are smaller (1000 to 10000 m^3) and used to bunker ferries/ships in the port and coast vicinities, whereas the latter are deployed for regional distribution of LNG and bunkering larger-size vessels. (The Danish Maritime Authority, 2012)

2.1.5 Regasification

Disbursals of the LNG, received on the terminal, are not made to the consumers in liquid form; globally, the natural gas deliveries to the doorstep are carried out through available existing pipeline infrastructure. So LNG also needs to be converted into normal pipeline gas, thereby undergoing a phase change, from liquid to gaseous state, through a process called regasification or vaporization.

Hence the LNG is returned to gas in a regasification facility at a receiving (or import) terminal. It is pumped into a double-walled storage tank, and is vaporized by warming at or above 5°C in a controlled environment. Vaporized gas is regulated for pressure and enters the national natural gas pipeline system. Residential and commercial consumers receive natural gas for daily use from local gas utilities or in the form of electricity. The quality of the gas is set by pipeline companies and end users. The process flow of an LNG import terminal, in general, is portrayed in Figure 2.1-16.

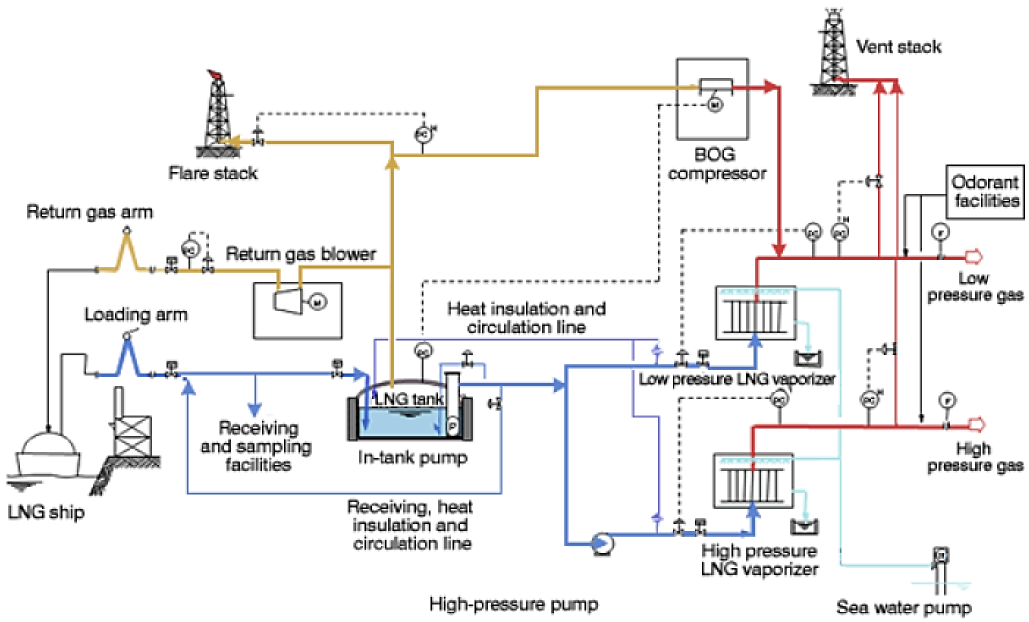

Figure 2.1-16 (Chiyoda Corporation, 2013): Work-flow of typical LNG import terminal

LNG coastline receiving terminals are typically equipped with loading arms, LNG storage, in-tank pumps, re-condenser, send-out pumps, vapourizers, boil-off compressor, and ancillary automation and safety systems, such as SCADA, ESD and F&G. At present, 20 terminals already exist while 32 others are in planning phase in Europe (Gasum Oy., 2013). Among the existing terminals, larger ones are situated in the United Kingdom, the Netherlands, and Belgium and potential terminals are expected by 2020 in France, Finland, Germany, Poland, the United Kingdom, and the Baltic countries (The Danish Maritime Authority, 2012).

Figure 2.1-17 (Henderyckx, 2013): The Zeebrugge LNG receiving terminal, Belgium

Zeebrugge and GATE constitute two main European LNG terminals termed as the entry points to natural gas grid of northwestern Europe, located at Belgium and Netherlands respectively (shown in Figure 2.1-17 and Figure 2.1-18). Zeebrugge is equipped with two regasification units having submerged combustion vaporizers (SCV) with a combined maximum send-out capacity of 1.7 million m^3 per hour at send-out pressure of about 80 barg (Fluxys Belgium SA, 2013), while GATE delivers natural gas at the rate of 16 BCM per annum with a total net storage capacity of 540000 m^3 (Gate terminal B.V., 2013).

Figure 2.1-18 (Anon., 2011): GATE Terminal B.V., The Netherlands

In addition to unloading and storage facilities, these terminals have loading arrangement for small scale LNG vessels (Renier, 2011), to be called as “LNG re-export terminals”.

2.1.5.1 Vaporizers

Vaporizers are the equipment which warm the received LNG to convert it back to gas using principle of extracting heat from water to heat the LNG. Following are the types used in LNG regasification terminals:

a. Open Rack Vaporizer (ORV)

These vaporizers take seawater from the adjacent body of water and make it flow down the outside of hollow panels, thereby heating the LNG that is flowing up through the interior of the panels in the opposite direction to the water stream, as shown in Figure 2.1-19. They are large and costly than gas-fired vaporizers (TOKYO GAS, 2013).

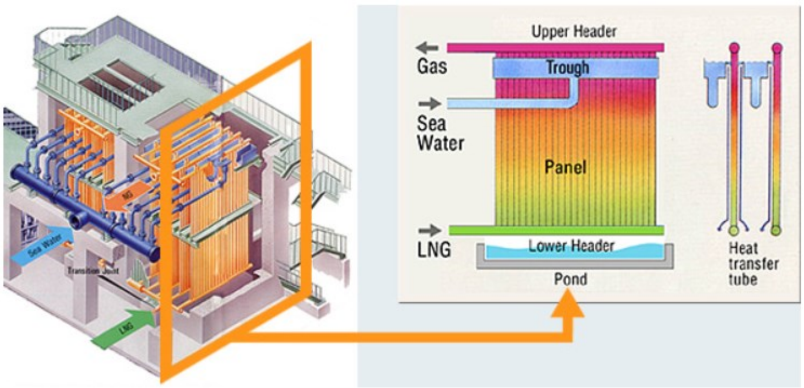

Figure 2.1-19 (TOKYO GAS, 2013): Open Rack Vaporizer

b. Submerged Combustion Vaporizer (SCV)

As shown in Figure 2.1-20, SCVs use natural gas/fuel gas to heat the LNG. The products of combustion are circulated in a bath of water where the LNG flows through an immersed bundle of tubes and is converted into gas. In this design, the LNG and the heat flow are in the same direction. SCVs use more energy than do ORVs and thus are more expensive to operate, but they create no water discharges.

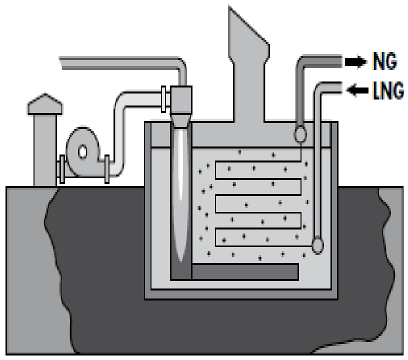

Figure 2.1-20 (China Petroleum Corporation, 2009): SCV scheme

c. Intermediate Fluid Vaporizer (IFV)

The IFV is characterized by its unique concept of three heat exchangers and the use of intermediate fluid.

By using intermediate fluid, the IFV is not subject to freezing and has a wider temperature range of the heating medium (Egashira, 2013). As illustrated in Figure 2.1-21, the process proceeds as:

1) Intermediate fluid (shell side) is vaporized by seawater (tube side).
2) LNG (tube side) is vaporized by the heat from the condensation of the intermediate fluid (shell side). Intermediate fluid is condensed by LNG on the surface of the tubes and dropped to the bottom of the shell.
3) NG (shell side) is heated by seawater (tube side) up to an ambient temperature.

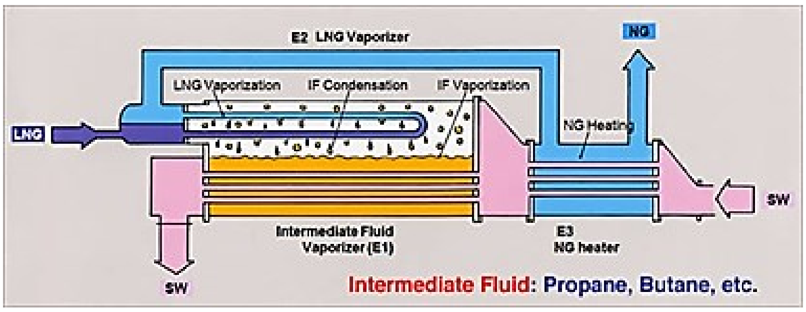

Figure 2.1-21 (KOBELCO, 2013) (Egashira, 2013) : IFV – schematic (originally patent of Osaka Gas Co., currently owned by Kobe Steel)

d. Shell and Tube Vaporizer (STV)

STVs (exhibited in Figure 2.1-22) are generally smaller in size and are cost competitive with SCV systems, but they require the provision of an external heat source. Heat is supplied to the LNG vaporizer by a closed circuit with a suitable heat transfer medium, typically a water/ glycol mix that is heated in a conventional boiler. These vaporizer systems usually require a stable LNG flow at design and turndown conditions, with provisions to prevent freeze-up within the vaporizer at low flow rates. (Tusiani & Shearer, 2007)

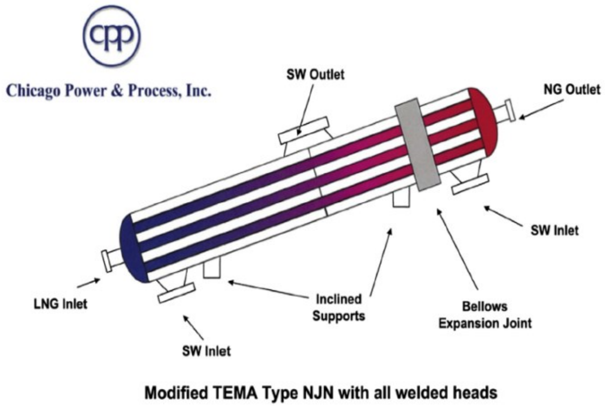

Figure 2.1-22 (Mokhatab, et al., 2014): An STV

e. Ambient Air Vaporizer (AAV)

These vaporizers take heat from the surrounding air for LNG regasification, and present more environmentally friendly version than ORV and SCV. Furthermore, AAV is economical as it can operate as standalone unit without seawater, fuel gas or intermediate fluid system. However, they require more space and tend to induce fog in atmosphere as the only impact on environment. They could also be in two configurations: direct air contact, and indirect air contact having an intermediate fluid. Air heat-exchanger can have natural draft or induced draft (Mokhatab, et al., 2014). Figure 2.1-23 shows a typical scheme of a direct contact AAV.

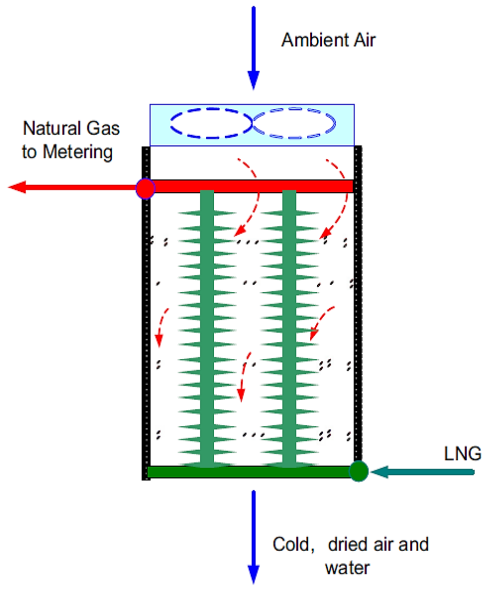

Figure 2.1-23 (Mokhatab, et al., 2014): A natural draft AAV – schematic

In addition to the above, there are some other techniques which employ fire/ furnace heating, electric heating, water steam heaters, water heaters by immersed gas burners, and isopentane heaters or other energy carriers.

By the end of 2012, world LNG receiving capacity is 649 MTPA from total 98 existing terminals (given in Figure 2.1-24), with Japan having the largest regasification capacity of 180 MTPA (International Gas Union (IGU), 2013). Overall, the total regas capacity is around three times higher than total LNG export size.

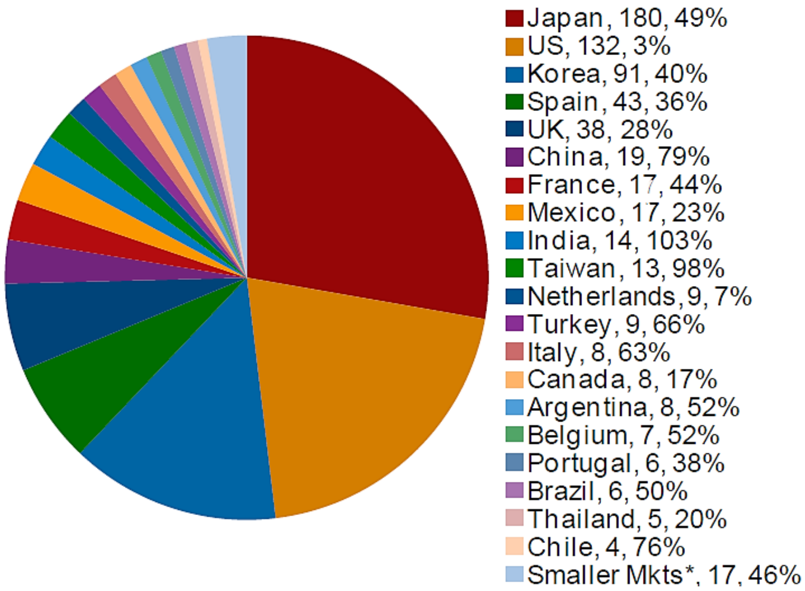

Figure 2.1-24 (International Gas Union (IGU), 2013): Country specific LNG Regasification Capacity (2012), Capacity (MTPA) and Utilization

The energy efficient terminals mostly use waste heat, air heat, and seawater for re-vapourization, while fire-heaters are expensive due fuel gas cost. Nevertheless, the thermal efficiency of regasification facilities and FSRUs stays 98-99% (Manninen & Koskela, 2012).

Currently, though new receiving terminals are getting on-stream while some older ones are upgraded, yet the global utilization of these terminals are typically less than 50% due to seasonal demand type of gas market; the fact is portrayed in Figure 2.1-25.

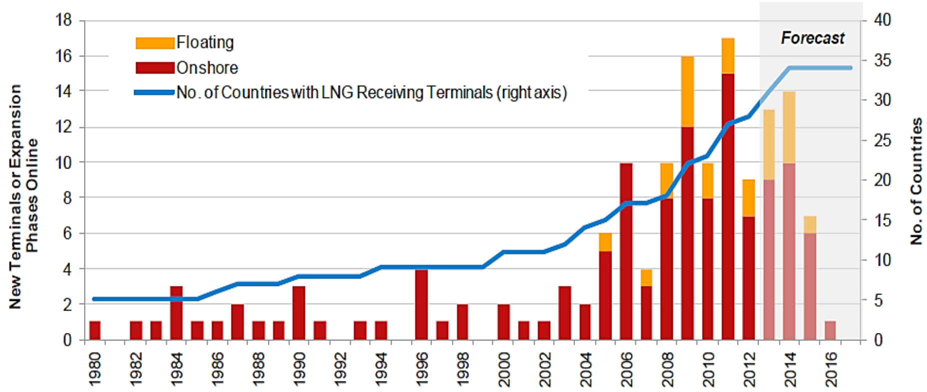

Figure 2.1-25 (International Gas Union (IGU), 2013): Commissioning of LNG Import Terminals, 1980-2017

2.1.6 LNG Engines – An Emerging Element of LNG Chain

The practice of LNG as a liquid fuel for ships in Northern Europe and heavy-duty trucks, and commercial vehicles in North America and Europe captures popularity. This increasing trend, spurred by high prices of oil and lower CO_2, NO_x and SO_x emissions of LNG, has made LNG engine sector an important constituent of LNG supply chain. Typically, this component has a position before the actual regasification of LNG at import terminal, just after LNG unloading. Instead of regasification, this LNG is dispatched to LNG-refueling stations in liquid form by rail or road.

Natural gas is widely used as a fuel in the internal combustion engines including the vehicles of various types, called as natural gas vehicles (NGVs).

Figure 2.1-26 (Sullivan, 2011): An LNG-powered heavy-duty truck getting refueled

Number of NGVs tends to grow faster in the world than in Europe reaching to around 17.73 million (NGVA Europe, 2013) in the world out of which 1.1 million belong to EU-25 countries and 1239 units are in Finland (NGVA Europe, 2013). NGVs store their fuel commonly in high pressure cylinders on board as CNG (compressed natural gas), but recent more efficient technology is the fuel storage as LNG/ cryogenic liquid storage, and some emerging techniques are in developing phase as well, such as methane-hydrogen blend storage, adsorbed NG (ANG), and metal-organic frameworks (MOF) (Fuganti, et al., 2012). Thus LNG-powered trucks are available in market and their number accelerates; Figure 2.1-26 displays an LNG-fueled truck getting refilled.

For road transport, some companies offer ex-works LNG engines:

1. Mercedes - Mercedes Econic (Mercedes-Benz Nederland B.V., 2013)
2. Volvo - FM MethaneDiesel LNG (Volvo Trucks, 2012)
3. Scania - P310 LNG (Scania CV AB, 2011)
4. Iveco – Stralis LNG Natural Power (Iveco S.p.A., 2012)
5. Truck/ Bus engines of Cummins Westport (Cummins Westport Inc., 2013)

Presently, LNG acts as a storage solution for NGVs; their engine works on the same principle as by CNG. Because of its high energy density, LNG has been of increasing interest for long-haul, heavy-duty trucks covering long distances, by eliminating the need to refill the fuel tank at short intervals, whereas CNG is considered in case of return-to-base vehicles, such as school buses, garbage trucks and local delivery transport. Compared to diesel, NG engines produce low CO_2 emissions per energy unit (MJ) of fuel owing to different H/C ratio. Though absolute potential of CO_2 reduction (by methane) is 23%, the actual reductions are in 10-18% range due to lower thermal efficiency of NG engines (AB Volvo Group Trucks Technology, 2012).

Figure 2.1-27 (VikingLine, 2012) (Mercator-Media, 2013): Viking Grace - Finland's first and world's largest LNG-fuelled passenger cruise-ferry, the €240m vessel can carry 3000 persons, built by STX Finland Oy. Turku and equipped with 4 Wärtsilä 8L50DF main engines traversed its first journey on 15.01.2013.

While LNG is already in use by the LNG carrier-ships, it tends to be a trendy marine fuel with 40 ships running on LNG (Semolinos, et al., 2013). Viking Grace and the upcoming NGL tanker by Wärtsilä are the latest Finnish examples shown in Figure 2.1-27 and Figure 2.1-28

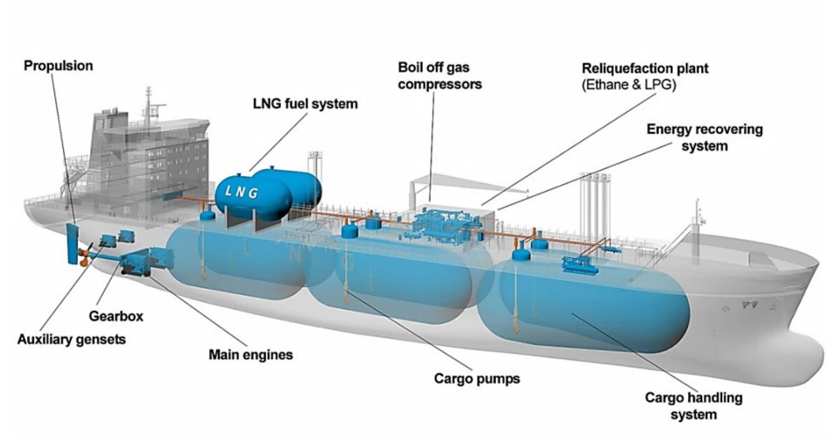

Figure 2.1-28 (Wärtsilä, 2013): Model of an LNG-fuelled ethane/NGL carrier to be supplied by Wärtsilä to Danish operator Evergas

The availability of LNG engines for power generation or LNG gen-sets is on the rise for environmental reasons; Figure 2.1-29 shows an LNG-powered marine gen-set.

Figure 2.1-29 (Peters Shipyards, 2012): First 100% LNG Scania Marine Gas Generator Sets delivered to Peters Shipyards, The Netherlands in December 2012 (Sandfirden Technics BV, 2012). LNG revolutionizes the inland shipping with emission reduction of more than 25% CO_2, 80% NOx, and no SO_2 and PM.

2.1.7 Other Futuristic Advancements

The issues of LNG supply chain flexibility and costs, regulatory considerations, onshore port logistic problems, shortage of suitable onshore sites and challenges in onshore projects have led the LNG industry to new concept of offshore liquefaction and regasification terminals.

Offshore-terminal solutions include shipboard regasification, Floating Storage and Regasification Units (FSRUs), HiLoad, fitting existing offshore platforms with LNG off-loading and regasification equipment, gravity based systems (GBS, which are almost identical to the liquefaction structures), and the Bishop Process (Tusiani & Shearer, 2007).

Figure 2.1-30 (Royal Dutch Shell plc., 2013) (LNG World News, 2012): Rendering of Shell's project "Prelude" the world's first FLNG and the largest vessel ever made, after completion by 2017, will produce at least 5.3 MPTA of liquids: 3.6 MPTA of LNG, 1.3 MPTA of condensate and 0.4 MPTA of LPG

Floating Storage and Regasification Units (FSRUs) can take two forms: a custom-built vessel or a converted LNG tanker permanently moored at the designated site. "Bonaparte" and Shell's "Prelude" are well-known FLNG (floating LNG) projects. "Prelude" concept is shown figuratively in Figure 2.1-30.

Converted LNG tankers use their cargo tanks as storage and are fitted with onboard regasification equipment, just like LNG shipboard regasification vessels. FSRUs generally require a minimum water depth of 150 feet for economic mooring (the FSRU may have one or two mooring points) and riser design (Mokhatab, et al., 2014). The FSRUs under consideration today will employ either a yoke or a turret system (a tower like revolving structure) to allow the structure to weather-vane (rotate) around a fixed point, depending on the prevailing water and wind currents. An LNG vessel would unload to the FSRU by using either a side-by-side or an end-to-end connection. The LNG would be stored in the FSRU's tanks before being vaporized onboard the structure and piped to shore via subsea gas pipeline (Tusiani & Shearer, 2007).

2.2 Natural Gas Quality and Interchangeability

"Natural gas" has a single generic name; however, it contains wide variations in composition and properties, and hence quality, depending on its origin in the world. Natural gas quality is the "attribute of natural gas dependent on its composition and its physical properties", as stipulated by ISO (ISO, 2001).

Natural gas finds its main use in combustion processes and then in the feedstock for the chemical industry. Since, all burners/ combustion equipment are designed for optimum performance with limited tolerance against a particular fuel type and characteristics, the appropriate fuels are required for them. Any change in the attributes, or gas quality specifications, causes concerns at the end-use applications, for instance, system performance (e.g., non-compliant environmental emissions), reliability (instability), safety (e.g., harm to employees, residents), integrity (e.g., pipe erosion, blade damage) and gas transportation operability, and energy billing requirements. If the import gas quality is out of required specifications, it could be modified either at the production plant, the reception/entry point or by relaxing the gas specification range. (Katz & Lee, 1990)

Gas quality may be altered in line with the prevailing standard specifications keeping in view its effect on end-use gas-fired devices. Generally, gas quality specifications are of two types (Kidnay, et al., 2011):

(i) The pipeline specifications, the limits which are meant to safeguard the pipe's physical structure and safe transmission of gas. These commonly include water and hydrocarbon dew points, and quantity of sulphur, oxygen, hydrogen.
(ii) The interchangeability specifications, which ensure that using the substitute gas will not affect the designed performance (safety, emissions) of any natural gas end-application. Heating value and specific gravity describe this ability of a gas.

Thus, gas interchangeability, being the sub-set of gas quality, determines whether a new gas burns securely and efficiently at domestic levels. Natural gas quality has been a regional or, at most, a national issue as gas was indigenously produced with the pipeline as the only means of transport, however, with the rise in cross-border trade of natural gas mainly though LNG raised the concerns of supply security due to the variance in gas quality produced by different sources. (BP, 2011)

Interchangeability could be defined as the ability of two different gases to be utilized in the same method with respect to the end use (mainly combustion) applications, such as in gas appliances and gas turbines. This characteristic is greatly affected by the changes in gas properties, including thermal/calorific value and specific gravity, coming from different gas sources. Interchangeability exists when the two gases behave almost equivalently with respect to combustion properties, efficiency and burner tip flame characteristics. The crux of interchangeability is based on identifying the heat input supplied to a burner though a nozzle/ orifice.

2.2.1 Natural Gas Quality Parameters

Typical combustion characteristics of natural gas include ignition point, flammability limits, theoretical flame temperature (stoichiometric air/fuel ratio), maximum flame velocity, relative density, heating value, and Wobbe index. However, while considering natural gas as fuel for internal combustion engine, another parameter "methane number" is counted as important fuel quality parameter related to engine knock behavior.

This work studies three most relevant natural gas features i.e., heating value, Wobbe index and methane number, which affect the quality of LNG, in particular. They are concisely explained here.

2.2.1.1 Calorific Value (Heating Value)

The amount of heat (chemical energy) produced during the complete combustion of a unit quantity (mass or volume) of fuel in the presence of oxygen (and the products of combustion are brought to the same conditions of pressure and temperature as of reactants) is called the calorific value or heat of combustion. Its SI units are J/kg and J/m^3. Water is obtained in the combustion products if hydrocarbon fuel is burned. Depending upon the amount of hydrogen in the fuel and combustion temperature, produced water is in the form of vapours. Therefore, a small amount of combustion energy (heat) is taken by water as the latent heat of vapourization.

Based on the phase of produced water, calorific value has been classified into two types.

The total quantity of heat generated by combustion reaction includes the heat of transformation (vapourization) of water, and is called the higher (or gross/ superior/ upper/ total) heating value (HHV). This latent heat stored in the vapour state of water can be recovered by condensing or cooling down the water back to its liquid state, and this heat of condensation increases the energy yield, known as HHV.

If the water remains in the vapour state, the available heat energy from combustion is termed as lower (or net/ inferior) heating value (LHV). This value is achieved after subtracting the latent heat of vaporization of water (in the combustion products) from the HHV. Usually, the final temperature of combustion products at exit point is higher than boiling point of water, thus losing the heat of water vapourization to atmosphere. Consequently, the LHV is obtained as the "effective" or sensible heat. Generally, Fuels are compared on LHV basis (Department of Energy Technology, KTH, 2010).

The net calorific value (or lower heating value) determines the fuel flow rate and is commonly used in calculations of gas turbines, and fired equipment such as engines and burners; whereas gross calorific value (or higher heating value) is utilized for custody transfer purposes or fiscal measurement in the gas industry. The HHV of pipeline gases can be measured, for example by continuous-recording oxygen bomb calorimeters, whereas LHV has no such method therefore it is a calculated value obtained from analysis of gas components (Katz & Lee, 1990). The quantitative relationship between HHV:LHV is approximately 1.108:1 in case of natural gas (Clarke Energy, 2013).

2.2.1.2 Wobbe Index

Also known as Wobbe Number (WN), this index is a comparative measure of thermal energy flow through a given nozzle size; it is not equal to heat input, and has units of energy per unit volume at a given pressure. The Wobbe Index (WI) is not related to the technical factors such as temperature, heat transfer coefficients or temperature gradients. If the Wobbe Index remains relatively constant between two gases they are called as interchangeable in case of heat flow in a burner.

As per American Gas Association Bulletin No. 36 (AGA Committee on Mixed Gas Research, 1946), "The Wobbe Index, or Wobbe Number, of a fuel gas is found by dividing the High Heating Value of the gas by the square root of its Specific Gravity relative to air. The higher the Wobbe Index of a gas, the greater the heating value of the quantity of gas that will flow through a hole of a given size in a given amount of time. In almost all gas appliances, the flow of gas is regulated by making it pass through a hole or orifice. The usefulness of the Wobbe Index is that for any given orifice, all gas mixtures that have the same Wobbe Index will deliver the same amount of heat."

$$WI = \frac{HHV}{\sqrt{SG}}$$

where

HHV is the higher heating value

SG is the specific gravity of natural gas

The Wobbe index can be Higher or Lower depending on use of higher heating value or lower heating value (LHV) in calculating it.

Fundamentally, Wobbe Index (also known as "interchangeability factor") compares the rate of combustion energy output of various fuel gases in gas appliances. Therefore, if two different gases have same Wobbe Index, they have the same energy output as well, for a specific valve position and pressure.

Experimental evidences (Karavalakis, et al., 2013) prove that emissions of various pollutants such as THC, CH_4, CO_2, CO, PM, particle number, formaldehyde, and acetaldehyde, have decreasing trend for vehicle engines fueled by natural gas with higher hydrocarbons, Wobbe Index and energy content (heating value).

2.2.1.3 Methane Number

Methane Number (MN) is a scale to measure the resistance of a gas fuel against knocking (detonation) in an internal combustion engine (analogous to octane number for petrol). It is product of various constituents present within the natural gas, such as methane, ethane, propane and butane.

Methane number is assigned to a test fuel based upon operation in a knock testing unit at the same standard knock intensity using methane and hydrogen as primary reference fuels, such that pure methane, which has high knock resistance, is allocated as the knock resistant reference fuel with index value (methane number) of 100. Pure hydrogen, which has low knock resistance and burns rapidly compared to methane, is used as the knock sensitive reference fuel with index value (methane number) of 0.

Methane number for natural gas corresponds to MON/RON indices for gasoline, and it is important measure for spark-ignition Otto-cycle engines and new compression-ignition dual-fuel engines which use natural gas and diesel fuel.

Engines manufacturers include MN in the fuel quality standards, in order to improve internal combustion engine performance. (Euromot, 2012)

Methane Number holds significant implications for companies linked to the natural gas supply, transmission, commercialization and engine applications. Thermal efficiency of a standard spark ignition engine increases with compression ratio. There is, however, an upper limit to the compression ratio which is due, primarily, to the fact that the fluid compressed in the cylinders is a mixture of fuel vapour and air, since the combustion mixture temperature increases on compression and if the compression ratio is high, it is possible that the phenomenon of detonation could occur due to the auto-ignition of the mixture. Detonation is known as engine knock and can lead to loss in power and damage to the engine (pistons, seals and cylinder head). The ability of a fuel to resist auto-ignition is a basic fuel characteristic.

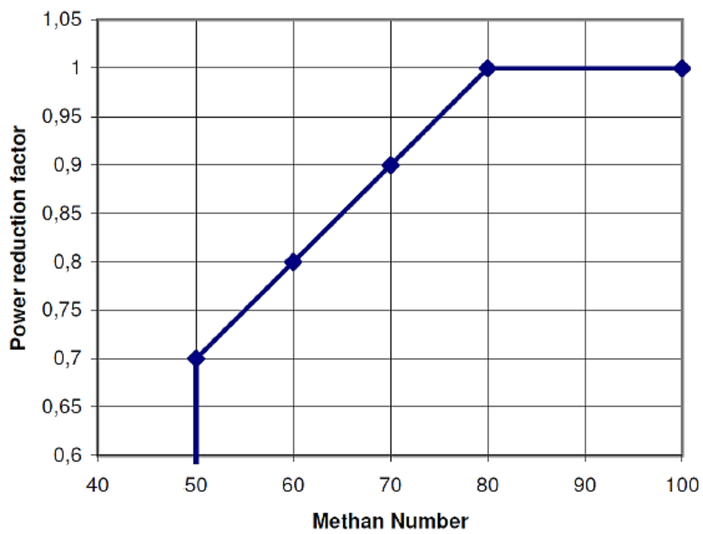

Figure 2.2-1 (Pon-Cat, Pon Equipment B.V., The Netherlands, 2013): Impact of Methane Number on Power Factor (MN calculated by Caterpillar)

Methane number affects the engine performance and emission efficiency. Figure 2.2-1 and Figure 2.2-2 illustrate this fact by showing impact of methane number on the engine power factor and acoustic velocity which has been taken as a measure of knocking in the engine. If knocking sound in the ICE is measured in terms of acoustic velocity, it has been observed that higher methane number decreases the sound velocity and hence the knocking tendency of the engine. This velocity is high for lower methane number fuels implying their low knock resistance and hence degraded engine performance. (Wise, 2013)

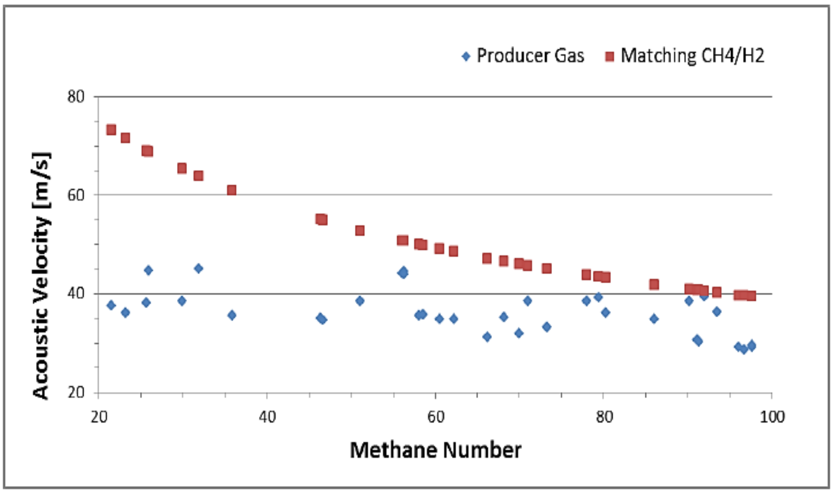

Figure 2.2-2 (Wise, 2013): Trend of Acoustic Velocity (knocking) with changing Methane Number

Lower methane numbers can be damaging to the engine due to high knocking. This is evident in the following graph (Figure 2.2-3) showing substantial reduction of knocking rate from 35% to 5% when the methane number is changed from 70 to 90 during a test on Scania marine engine running on LNG.

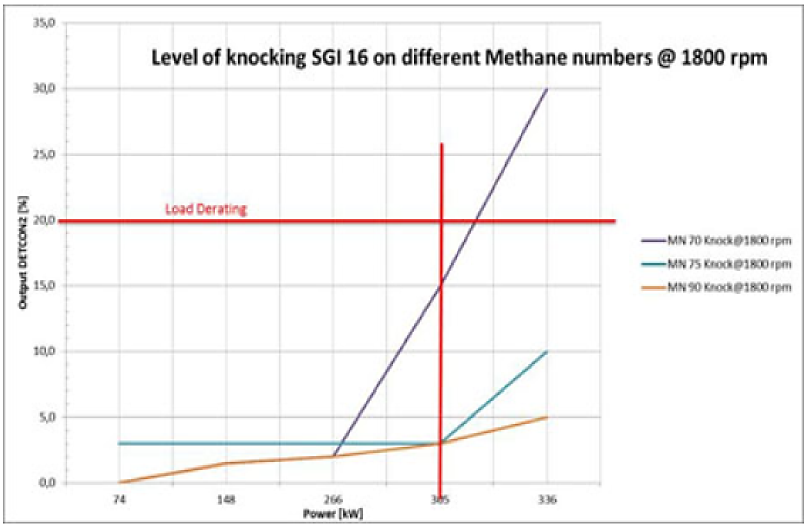

Figure 2.2-3 (Sandfirden Technics BV, 2013): Testing result (% knock detection output v/s engine power) of Scania SGI-16M Marine gas engine against different LNG qualities with MN 70, 75 & 90

Methane Number Calculation

Methane number is not a thermodynamic property of gas, so it is experimentally measured; it cannot be calculated using any equation of state (EOS).

There is a difference in the measured and calculated MN though MN is less sensitive to fuel effects at its lower end range; nevertheless, the composition-based calculation of MN produces reasonably comparable results (Falkiner, 2003). Currently, no international standard exists to test the knock rating of natural gas as the test methods in practice are based on liquid fuels.

Several methods are in utilization for the purpose to calculate the methane number; some of them are described here.

GRI Method

In order to determine the methane number, the Gas Research Institute (GRI), USA, applied the ASTM D2700 standard octane rating method to various natural gas fuels. It uses motor octane number (MON) to compute MN.

- Motor Octane Number (MON) of the natural gas fuels was obtained.
- Two mathematical correlations were developed to estimate the MON rating of a natural gas fuel based on its composition:
  - Linear Correlation.
  - Hydrogen/Carbon Ratio.
- From MON, Methane Number (MN) is calculated.

Both correlations are included in an informative annexure of ISO 15401-1:2006 “Natural gas – Natural gas for use as a compressed fuel for vehicles, Part 1: Designation of the quality”.

The following formula is used for MN calculation.

$$MN = 1.445\ MON - 103.42$$

The correlation is not linear, and as a result the equation cannot be used, in an inverse way, for MON calculation. The MN depends on the calculation method since both methods calculate different value of MN. If the difference between the two MN-results is more than 6, they are considered incorrect or erroneous; so a test method should be used in that case for determining the MN.

MON by Linear Correlation Method

Calculation of MON is carried out from composition by this relation.

$$MON = 137.78\, C_1 + 29.948\, C_2 - 18.193\, C_3 - 167.062\, C_4 + 181.233\, CO_2 + 26.994\, N_2$$

where C_1, C_2, C_3, C_4, CO_2 and N_2 are the mole fractions of corresponding components.

The method cannot consider heavier components than butane.

MON by Hydrogen/Carbon (H/C) Ratio Method

This method uses the equation developed in SAE Paper 922359 (Kubesh, et al., 1992), which is

$$MON = -406.14 + 508.04\, R - 173.55\, R^2 + 20.17\, R^3$$

where R is the ratio of hydrogen atoms to carbon atoms in the gas, H/C.

Theoretically, the method can consider heavier components than butane.

CARB (California Air Resources Board) Method

CARB method, mostly utilized in North America, is also the H/C ratio technique, and uses the same above SAE equation but calculated the MN from following relation (CARB, 2001) (CARB, 1993):

$$MN = 1.624\, MON - 119.1$$

The MN calculated by CARB method is commonly higher than that by AVL method. In a study by Southern California Gas Company, MN on a group of test gases was measured firstly and then it was calculated using both methods. It was observed that CARB method produced 8.6% higher MN than the actual test value and 7.9% higher value than AVL method, whereas AVL procedure yielded 0.6% lower MN than actual test values (Southern California Gas Company, 2005).

AVL Method

German Anstalt für Verbrennungsmotoren's Professor Dr. List (AVL) used a methodology similar to that in ASTM D 2699-97. In 1970s, AVL Inc. developed a method to calculate the methane number, based on experimental measures of binary and ternary gas mixtures of components C_1 up to C_4, H_2, CO_2, N_2 and H_2S (Andersen, 1999). The MN is calcualated by combining the MN of each of these 3 sub-mixtures (Alamia, et al., 2012). Though this method is popular in the industry, yet it yields fairly accurate results (compared with experimental results) if nitrogen is excluded from the gas composition (Euromot, 2012). This MN calculation tool is proprietary item of M/s AVL Inc. and is available under license as software named "Methane".

- The exact algorithm is confidential and property of AVL Inc.
- There is different commercial software available.

Engine Manufacturer Methods

Numerous manufacturers have developed their own calculation method, based on the available ones and experience. They include Wästsilä, Volvo, MAN, Iveco, Cummins, Scania, Caterpillar, and many others. Several brands, for instance Cummins Westport, have online methods accessible through their website (Cummins Wesport, 2013).

There are only two known public method for the calculation of MN (ISO 15403-1:2006, currently under revision, ISO/TC 193). MN calculation methods give different results. If MN would be included in a natural gas/biomethane quality standard single calculation method should be agreed, which should be made public and the range included should wider a low minimum limit. (Gas Infrastructure Europe (GIE), 2012).

If a narrow MN would be included, it could endanger the security of supply of the natural gas to European market and reduction of gas sources mainly the most flexible, LNG. This will add quality adjustment cost to the gas system that, at the end, will be paid by end-users, reducing the benefit of gas quality harmonization.

E.ON's GasCalc® Method

Conventional AVL method calculates MN with sufficient reliability, however it does not account for nitrogen in its calculation. This issue is addressed in E.ON's patent software GasCalc®.

GasCalc® 2.3 is multidimensional software tool with many computing modules for calculation of physical natural gas properties, such as combustion, methane number, SGERG, AGA8, transport properties and compressors. For methane number calculation of a given gas blend, its Methane Number Module contains two methods specified by functions named as MN_21 and MN_s. The former computes MN by AVL Method from analysis of 21 components by accepting input in mol- or volume-% i.e., xi(21) [mol%], whereas the latter adopts short, Simplified Method from partial analysis (superior calorific value, normal density, CO_2 mole fraction) of 21 components i.e., Hsv [MJ/m³], ρn [kg/m³], xCO2 [mol%]. Compositional and magnitude limits are imposed for every gas constituent and input property, which are covered by two application ranges, called as the "extended range" and "limited range" with an output uncertainty of 6 and 2 MN respectively (E.ON Ruhrgas AG, 2012). Simplified method is available for limited range only, and the AVL method takes components only uptill butanes for the limited range. Inert components such as CO_2 and N_2 increase MN while higher hydrocarbons decrease it, the reason for greater methane number for L-gases than that of H-gases.

The technique is duly supported by Euromot and they recommend the Simplified Method in this tool (Euromot, 2012).

Revised CEN Method

Work is in progress by CEN for European Standard method to calculate MN of gaseous fuels, mainly H-type natural gas without un-saturated hydrocarbons and hydrogen based on original data if AVL with amendment by Motoren Werke Mannheim GmbH (MWM). (CEN/TC 234/WG 11, 2013)

The standard is yet in draft mode; its method is composed of 5 steps:

1) The composition of the gaseous fuel is simplified by converting hydrocarbons of carbon number greater than 4 into an equivalent amount of butane. The simplified composition is reduced to an inert-free component comprising four hydrocarbons (methane, ethane, propane and butane), and an inert component, containing nitrogen and carbon dioxide. The simplified mixture is normalized to 100 % mol/mol.
2) The inert-free component is sub-divided further into three partial ternary mixtures.
3) The composition and fraction of the three partial mixtures is adjusted iteratively so as to minimize the difference between the methane numbers of each partial mixture.
4) The methane number of the inert-free mixture is determined from the weighted average of the methane number of the three partial mixtures.
5) The methane number of the gaseous fuel is calculated by correcting the methane number of the inert-free mixture to allow for the presence of inerts in the original fuel gas.

The method is still under development and consideration by CEN.

2.2.2 Gas Interchangeability Indices

Interchangeability Index is an indicator to measure specie's compatibility, conformity, adaptability, flexibility or exchangeability (so called as "interchangeability") with other alternates to substitute its end uses. This index is in fact a measure to set up criteria for interchangeability, and it is basically the numerical interpretation of the observations/ evidences of physical phenomena (BP, 2011).

Traditionally, several techniques have been discovered to know and quantify interchangeability though research and experiment, such as the Wobbe Index, American Gas Association (AGA) Bulletin No. 36 and the Weaver Indices Method. But none of these have been widely used, except the Wobbe Index (Foss, et al., 2004). The Wobbe Index is calculated by dividing the saturated (lower) calorific value by the square root of the specific gravity of the gas under consideration.

Natural gas interchangeability has been historically investigated by employing numerous modeling techniques; Single Index and Multiple Index are the main models among them. (Halchuk-Harrington & Wilson, 2006)

Different indices and index limits were developed mostly on empirical basis. Although Wobbe Index is the most commonly (but not universally) accepted interchangeability parameter, several other parameters have been in use across the world, such as the following.

- Wobbe Index or Wobbe Number (WI or WN)
- AGA Indices, which comprise
    - Lifting Index
    - Flashback Index
    - Yellow-tipping
- Weaver Indices, which comprises
    - Lifting Index
    - Flashback Index
    - Yellow-tipping Index
    - Incomplete Combustion Index
    - Primary Air Ratio
    - Heat Rate Ratio
- Modified Wobbe Index or Modified Wobbe Number (MWI or MWN)

$$MWI = \frac{LHV}{\sqrt{SG \times T}}$$

where

LHV is lower heating value

SG is the specific gravity and

T is the absolute temperature of gas (fuel) delivered to turbine/ engine.

- Dutton's Soot Index (SI) (Cagnon, 2006)
- Incomplete Combustion Factor (ICF)
- Delbourg's Combustion Potential
- Light-back
- Higher (or Upper) Heating Value or Gross Calorific Value (HHV or GCV)
- Lower Heating Value or Net Calorific Value (LHV or NCV)

- Relative Density or Specific Gravity (RD or SG)
- Methane Number (MN)

AGA indices were based on the study AGA Bulletin No. 36 in 1946, which was improved further by E.R. Weaver (Foss, et al., 2004). Presently, Dutton's indices are in practice in UK with some amendments, and certain ranges of these indices have been permitted by regulatory bodies (Marcogaz, 2002). ICF < 0.48 and SI < 0.6 are the allowable limits by UK GS(M)R.

As the interchangeability concern gained worldwide attention, particularly in Europe and Asia, the Wobbe Index has received the widest application and popularity due to the advent of quick and reliable input data, its relative ease of calculation and predictability characteristics. It is simple to interpret and is easily applied in field operations.

In the presence of a number of indices, it seems that until further research and testing would yield a newer and more accurate and practical measure of gas interchangeability, until then the Wobbe Index should be applied domestically as the standard for interchangeability. (Foss, et al., 2004)

The quality specifications and the natural gas industry throughout Europe are quite sophisticated compared to US standards. Though they vary country by country, the modern day European Union has long employed the Wobbe Index, dew point control and other measures not commonly seen in the United States. Though commercial frameworks in the European Union gas industry are undergoing deregulation, unbundling and open access, from a technical and quality perspective, the EU appears somewhat more advanced than the US, most likely attributable to its history of diverse traditional gas supply and LNG via importation. (Halchuk-Harrington & Wilson, 2006)

While these practices and standards have been in place for some time, their application has differed on a country to country basis. As such, the European Union is currently challenged to reach consensus on harmonization of such gas quality standards that will promote cross border and intra-union commerce.

2.3 Impact of Altered Natural Gas Quality on End-use Applications

The end-use applications can be divided into two groups, combustion applications and non-combustion applications. Combustion applications could be either simple burning in burners, combustors, boilers, or in the internal combustion engines.

The impact on first group could be described as the following combustion specific phenomena

1) Auto-ignition or Knocking in the engines
2) Flame instability (fluctuation and vibration)
3) Lifting
4) Flashback
5) Flame failure (Blowout)
6) Yellow tipping
7) Incomplete combustion (CO production)
8) Emission production (NOx, SOx, unburnt HCs)

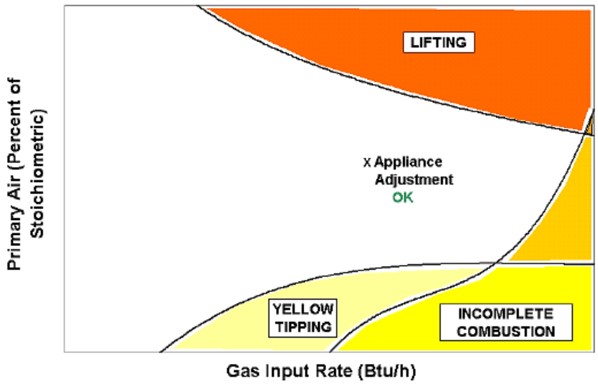

Figure 2.3-1 (Halchuk-Harrington & Wilson, 2006): Burner Curve, the basis of interchangeability calculation

As gas composition affects the gas density and stoichiometric air-fuel ratio, it has an important influence on the performance of the exhaust emission system. The middle white area shown in the atmospheric burner diagram in Figure 2.3-1 for the gas input rate vs primary air, is the safe operating zone for the gas appliance.

For engines, variation in natural gas composition or replacing the methane content with the higher hydrocarbons can cause a knock and engine damage due to lower knock resistance of the fuel as is referred in Figure 2.3-2. Moreover, with addition of hydrocarbons, the measured equivalence ratio (φ) to the engine is upset which changes the burn rate of the air-fuel mixture, thereby affecting the emissions and efficiency. The inert components such as nitrogen and CO_2 may produce issues like misfire in the engine. Consequences of varying natural gas composition depend on the engine type (fuel delivery system, combustion chamber design), engine control loops (open or closed, carburetor of fuel injection) and engine power level as higher power decreases knock level. (Wise, 2013)

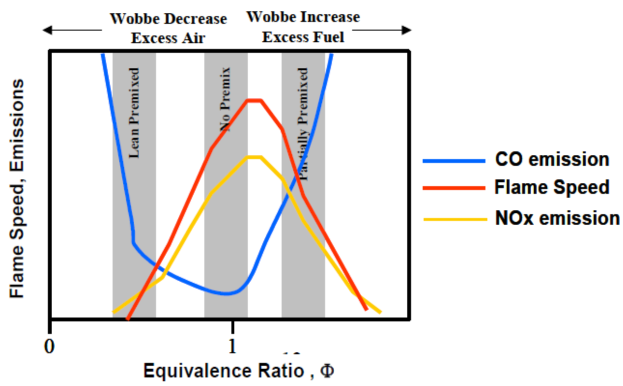

Figure 2.3-2 (Kuipers, 2005): Wobbe effect on flame speed

Higher NOx and CO emissions, greater soot production would be caused by domestic appliances such as boilers, cookers, industrial burners, turbines, internal combustion engines. Fuel cell would cause carbon deposition and non-energy uses such as chemical feedstock may have unscheduled shutdowns, and various plant implications (Kavalov, et al., 2009). Efficiency reduction, poor operability, knock intensity and unplanned outages are other impacts for the engines, turbines and industrial burners. Figure 2.3-3 exhibits the enhanced rate of NOx emission with decrease in methane number.

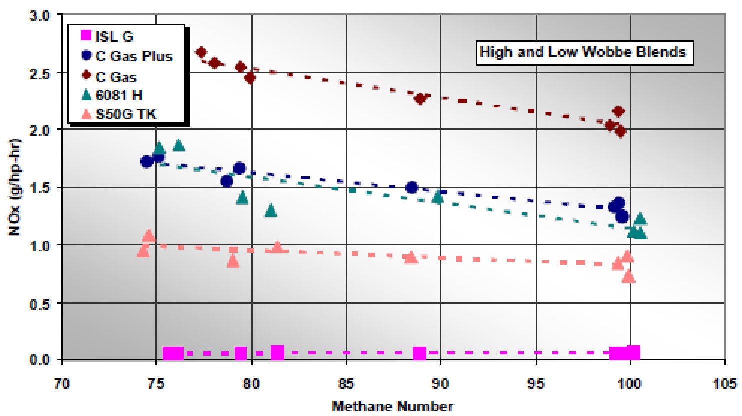

Figure 2.3-3 (Southern California Gas Company, 2009): Impact of MN change on NOx emissions

If the Wobbe index of a fuel is increased, it reduces the air gas ratio and increases the power input, thereby causing production of CO, soot and incomplete combustion along with knocking, early ignition and NOx emission in premix turbines. On the other hand, a reduced Wobbe number produces flame lift, and high CO production in the burners. Effect of change in Wobbe on the NOx emissions can be observed in Figure 2.3-4. (Marcogaz, 2008)

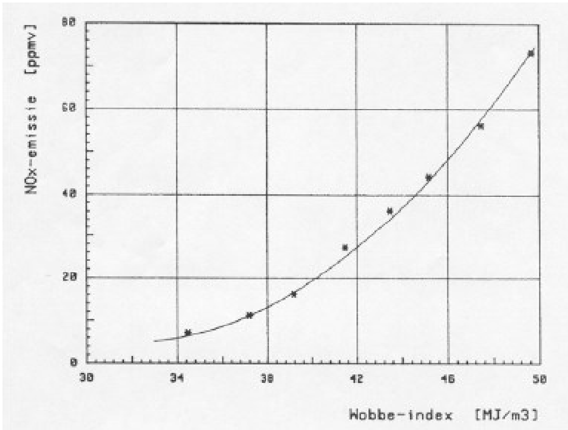

Figure 2.3-4 (Marcogaz, 2008): Impact of variation in Wobbe number on NOx emission produced by lean-premixed burner

2.4 Gas Interoperability and Synchronization Efforts

The concept of interchangeability is not older than that of fuel flexibility; main activity in this field started around three decades ago in the USA and Europe. Because of limited gas trading, no need was realized at that time for an internationally harmonized interpretation of natural gas interchangeability. During that period, there were advances in the UK, as it faced acceptance of divergent quality indigenous gases (available at UK Continental Shelf) to its grid. Consequently, the UK gas industry had to develop gas suitability standard initially for residential gas appliances (BP, 2011). However, the issue rose again when, because of diminishing fossil oil reserves, most of the developed nations started importing LNG. This trend re-intensified the interoperability of the substitute imported gases in the local gas infrastructure. The following paragraphs concisely describe major research efforts for gas quality homogenization and interchangeability in different parts of the world.

In the United States, the fuel flexibility was studied as early as 1930's by appliance testing programmes at various points of time. With recognition of interchangeability as “fundamentally an end-use issue” related to combustion, the testing programmes were almost exclusively focused on domestic and light commercial gas uses (Williams, 2006). AGA’s Research Bulletin 36 (Interchangeability of Other Fuel Gases with Natural Gases) in 1946 is base of this study improved by E.A. Weaver. Lately in 2005, the issue was investigated by organizing a joint NGC+ workshop which converged to an NGC+ White Paper recommending an interim guideline of ± 4% Wobbe Index tolerance for local historical average gas, subject to a maximum Wobbe Index of 1400 btu/scf, a maximum calorific value of 1110 btu/scf, maximum 1.5 mol% butanes+, and maximum 4 mol% total inerts (NGC, 2005).

In the Far East, Japan is the largest LNG importer, with typically high energy contents. While high CV regasified LNG is supplied to urban regions, sparsely populated areas are provided with the LPG. A governmental plan named as Integrated Gas Family (IGF) 21 Plan is intended to integrate the LNG and LPG supplies. Though China has no natural gas quality standards on national level, the China Natural Gas Standardization Technical Committee (CNGSTC), established in 1999, is working on this agenda with the development of some measurement, sampling and testing standards in line with ISO norms. Chinese national standards for LNG are also in progress by LNG Standardization Technology Working Group. (BP, 2011)

Situation in Europe

Europe has a variety of natural gas qualities with wide variation. However, on a joint level, Europe has neither natural gas nor biomethane (methane obtained from non-fossil/ renewable origin) automotive market fuel specifications (as of December 2012) (NGVA Europe, 2013), whereas diesel (EN 590), gasoline (EN 228), LPG (EN 589), and even FAME-methyl-ester (EN 14214) already have their own specifications. This situation is quite relevant, as design of engines should base its work on a known fuel composition and its potential variability (International Energy Agency (IEA) - Advanced Motor Fuels (AMF), 2012). The same holds true for LNG, while engine manufacturers have already defined the gas (LNG or biomethane) quality standards for their products. The Swedish standard SS 15 54 38 is the only standard in Europe for biomethane directly used as a vehicle fuel (Grahn, 2013).

Gas Quality Standardization

Gas appliances were started to be standardized in the wake of EU's Gas Appliance Directive or GAD (Directive 90/396/CE) enforced in 1993, which obligates their certification against a general European standard EN 437 "Test gases, test pressures, Appliance categories".

As concerns the interchangeability, Wobbe Index and EN 437 are utilized as the measure and the standard for this in Europe. EN 437 classifies the gases in 3 families [manufactured gas, natural gas, and LPG (Schweitzer & Cagnon, 2012)] based on Wobbe range (Gross Wobbe Index at 15°C, 1013.25 mbar); each family is further divided into groups. Natural gas has three groups namely (CEN, 2003):

- Group H, for a gas of Wobbe Index range 45.7 – 54.7 MJ/m^3
- Group L, for a gas of Wobbe Index range 39.1 – 44.8 MJ/m^3
- Group E, for a gas of Wobbe Index range 40.9 – 54.7 MJ/m^3

The gas appliances could then be tested for and certified against the H, L or E gases, with proper marking for the European market. However, the issue sustains, since the Wobbe range of natural gases used in various countries largely differs from one another and from EN 437 limits, due greatly to the different local and national ranges developed according to the nature of gas sources in different counties long before the harmonization regime. Thus, many of them possess rather contrasting natural gas quality as could be observed in following figure, which poses harsher gas interchangeability challenges across borders. Figure 2.4-1 explicitly shows the range of Wobbe index in the EU.

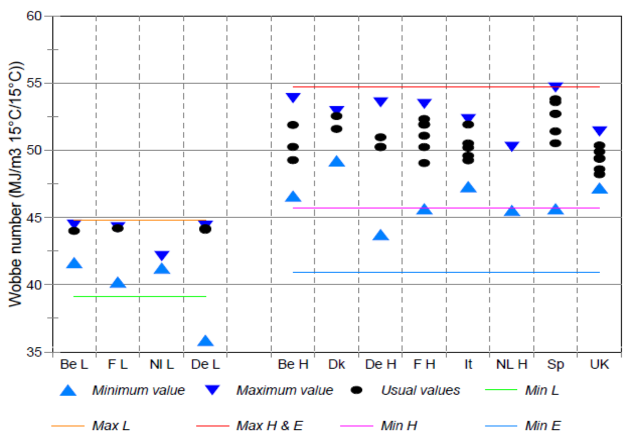

Figure 2.4-1 (Marcogaz, 2002): Range of Wobbe Index in the EU

2.4.1 Marcogaz Contribution

Marcogaz, the Technical Association of the European Natural Gas Industry, conducted a study in 2002 on the current state of affairs of gas quality specifications in 8 European nations (Belgium, Denmark, Germany, France, Italy, Netherlands, Spain and UK) representing over 84% of EU gas consumption. The study presented vast differences in the quality of natural gas specified; the analysis is depicted in Figure 2.4-1. (Marcogaz, 2002)

These attempts did not meet much success, as though new devices could be fully EN 437 compliant, yet these specifications did not resolve the combustion parameters problem for the appliances after the aging and those which are field-adjusted.

As per Marcogaz, natural gases in Europe are separated between the L and H quality as defined in EN 437. These "high" and "low" classes of gas are non-interchangeable and thus supplied in detached networks. The only source of L-Gas is the Netherlands, whereas H-gases have numerous origins including the North Sea, Russia, Algeria and Nigeria. Major of other reasons for gas quality difference in H-gases is the transportation of natural gas to Europe, some of them are liquefied thus stripping the gas of a number of heavier hydrocarbons. (Marcogaz, 2002)

Table 1 (Marcogaz, 2003): First European joint gas quality parameters, proposed by Marcogaz in 2003

Parameter	Unit	Combustion ref. condition 15°C Volume ref. condition 15°C, 101.325 kPa		Combustion ref. condition 25°C Volume ref. condition 0°C, 101.325 kPa	
		Min.	Max.	Min.	Max.
Wobbe Index (Gross)	MJ/ m^3 (kWh/m^3)	47	54	49.54 (13.76)	56.92 (15.81)
Relative Density		0.5548	0.7	0.5549	0.7001
Gross Calorific Value (derived from above values)	MJ/ m^3 (kWh/m^3)	35.01	45.18	36.91 (10.25)	47.63 (13.23)

H-gas is common throughout Europe. L-gas is distributed in only four (4) countries; the Netherlands, France, Belgium and a small area in Germany. In these countries L-gas and H-gas are distributed in separate networks. In France, Belgium and Germany the L network is a regional network. In the Netherlands, the L network serves domestic, commercial and small industrial customers while H-gas is distributed to larger industrial customers. Gases with widely varying composition are blended to a fairly narrow band of Wobbe Index values. In 2003, Marcogaz Working Group "Gas Quality" suggested the ranges (given in Table 1 above) of natural gas interchangeability parameters as common specifications to be used in Europe (Marcogaz, 2003). Marcogaz proposal was not acceded to on a joint European level.

2.4.2 EASEE-gas CBP

Technical harmonization of the energy is essential for interoperability among European nations; therefore, although identifying this issue in 2001, the first effort was the development of EASEE-gas quality specifications in 2005.

Founded in 2002 with the support of an EU body, the European Gas Regulatory Forum (Madrid Forum), European Association for the Streamlining of Energy Exchange (EASEE)-gas worked to set up CBP (common business practices) i.e., rules to be taken as reference and acceptable to all members, for the harmonization of gas quality by presenting its first proposal in February 2005 which was later revised in November 2008 (EASEE-gas, 2008). Theses specified values (which are for H-gases by their Wobbe range) are the minimum number of gas quality parameters without odourants applicable at the cross border gas entry and exit points. This effort, however, could not address the combustion parameter issues. (Schweitzer & Cagnon, 2012)

The EASEE-gas CBP values are given in Table 2.

Table 2 (EASEE-gas, 2008): EASEE-gas CBP for gas quality across Europe

Parameter	Unit	Min.	Max.
Wobbe Index (Gross)	kWh/m^3 (MJ/ m^3)	13.6 (46.44)	15.81 (54)
Relative Density	m^3/m^3	0.555	0.700
Total Sulphur	mg/m^3	-	30
H_2S+COS Sulphur (as S)	mg/m^3	-	5
Mercaptan Sulphur (as S)	mg/m^3	-	6
Oxygen	mol %	-	0.001
CO_2	mol %	-	2.5
Water dew point	°C at 70 bara	-	-8
HC dew point	°C at 1 – 70 bara	-	-2

*Original energy units kWh/m^3 are at combustion reference temperature of 25°C, and the volume unit is at reference conditions of 0°C and 1.01325 bar (a). Unit conversion to MJ is made by ISO 13443:1996 (Natural Gas – Standard reference conditions) recommended reference conditions.

2.4.3 CEN and GASQUAL Project

Subsequently, European Commission attempted to develop European Standards (EN) for H-gas regarding interchangeability of gases with focus on combustion parameters and the Wobbe Index. For the purpose, EU gave mandates to the 3 European Standardization Bodies (CEN/ CENELEC/ ETSI). CEN was invited through mandate M/400 in order to set the broadest possible gas quality standards of H-gas across the EU in line with the Directive 2003/55/EC of the European Parliament and of the Council to build a unified viable gas market in Europe. The mandate was composed of two phases; first phase contained analysis of the combustion parameters (i.e., gross Wobbe Index and relative density) in the existing gas appliances, and second phase involved the declaration of a European gas quality standard taking into account both the combustion and non-combustion parameters.

Besides, for the last decade, some EU study projects led by European Associations such as Marcogaz and EASEE-gas (e.g., drafting the Mandate M/400, GASQUAL project and EU Gas Quality Implementation Pilot Project) supplement such actions. This pilot project is directed towards adopting a wide Wobbe range by 5 countries. Work group CEN/TC 234 WG 11, responsible for the second phase of Mandate M/400, is currently working out an H gas EU standard specifying main gas characteristic (Marcogaz, 2013).

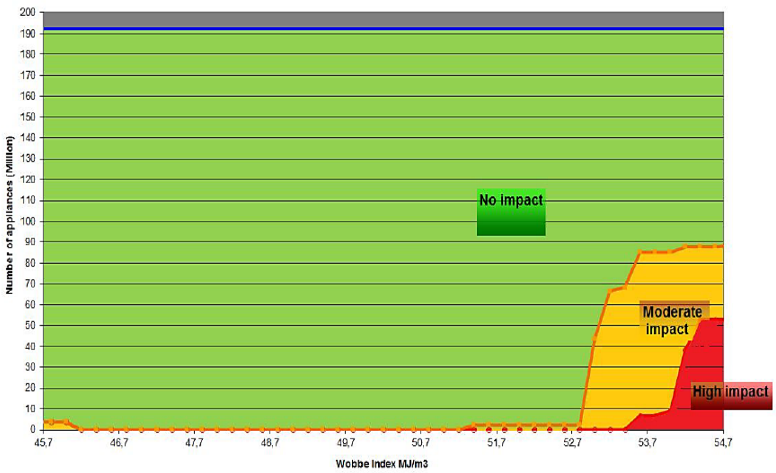

Figure 2.4-2 (Schweitzer & Cagnon, 2012): Wobbe effect on Overall EU gas appliance market

GASQUAL is actually focused on determining the impact of change in gas quality on the end-use gas appliances/ applications in the EU (GASQUAL.EU, 2013). Spearheaded by CEN working group CEN BT WG 197, GASQUAL studied this effect on more than 200 million appliances which complied with EU's Gas Appliance Directive (Directive 90/396/CE). Figure 2.4-2 represents the Wobbe effect on the gas appliances in EU. The project concluded that the appliance adjusted in field will be affected in case of Wobbe index variation, and a number of appliance categories would under-perform at the highest Wobbe range for a fuel gas as per the analysis carried out in Figure 2.4-2.

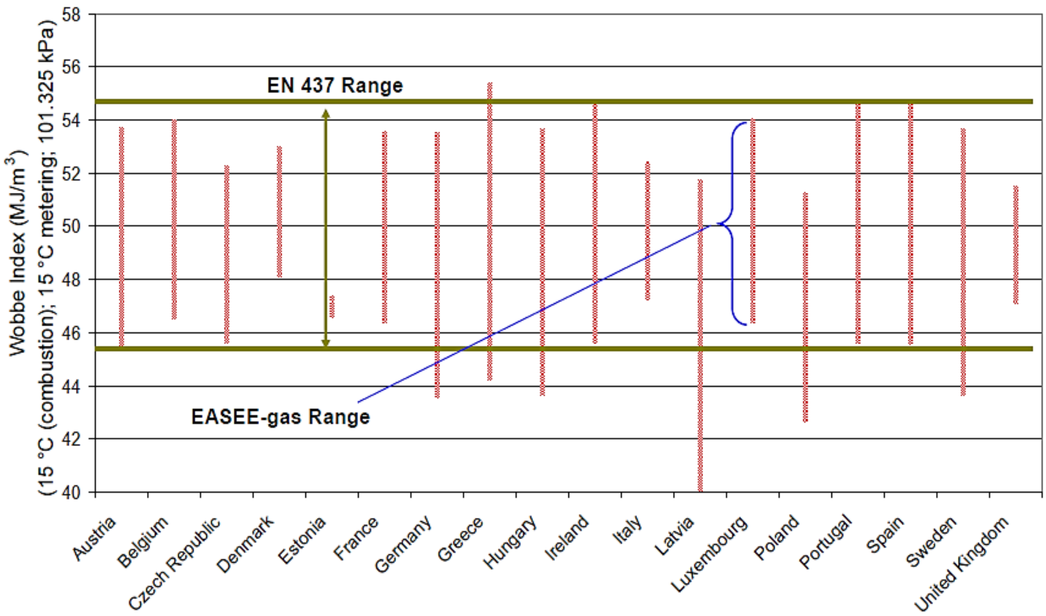

Figure 2.4-3 (Kimpton & Brown, 2010): European acceptable natural gas 2H family (N.B. Poland is E-gas range not H-gas.)

A comparison of European natural gas Wobbe index (Figure 2.4-3) portrays that both EASEE-gas and EN 437 do not completely encompass the existing members' transmission gas quality. With the large difference, Estonia has the narrowest band and Greece the widest (excluding Latvia as their range appears to include both H- and L-gas). There are four members that can accept gas quality with Wobbe Index greater than the EASEE-gas upper limit and eleven members with Wobbe Index lower than the EASEE-gas lower limit.

CEN's technical committee is on work to set up joint European gas quality standard, Figure 2.4-4 shows the latest specifications proposed by CEN which forwarded for comments from member states.

Parameter	Unit	Limits		Relevant standards
		Min	Max	
Wobbe Index	MJ/m^3	46,44	54,00	EN ISO 6976, EN ISO 15971
Relative density	no unit	0,555	0,70	EN ISO 6976, EN ISO 15970
Total sulfur without odorant	mg/m^3	not applicable	20	EN ISO 6326-5, EN ISO 19739
Hydrogen sulfide + Carbonyl sulfide (as sulfur)	mg/m^3	not applicable	5	EN ISO 6326-1, EN ISO 6326-3, EN ISO 19739
Mercaptan sulphur without odorant	mg/m^3	not applicable	6	EN ISO 6326-3, EN ISO 19739
Oxygen	mol/mol	not applicable	0,001 % or 1% (see below)	EN ISO 6974-3, EN ISO 6974-6, EN ISO 6975
	At network entry points and cross border points between CEN member states the maximum mole fraction of oxygen shall be no more than 0,001 % mol/mol. However, at entry points where the gas entering will not flow to another member state's network through a cross border point, a higher National limit of up to 1 % mol/mol may be applied, provided that the network is a dry network and not connected to installations sensitive to higher levels of oxygen, e.g. underground storage systems.			
Carbon dioxide	mol/mol	not applicable	2,5 % or 4% see below	EN ISO 6974-1 to -6, EN ISO 6975
	At network entry points and cross border points between CEN member states the maximum mole fraction of carbon dioxide shall be no more than 2.5 % mol/mol. However, at entry points where the gas entering will not flow to another member state's network through a cross border point, a higher National limit of up to 4 % mol/mol may be applied, provided that the network is a dry network and not connected to installations sensitive to higher levels of carbon dioxide, e.g. underground storage systems.			

Figure 2.4-4 (CEN/TC 234/WG 11, 2014): Recent CEN proposal of European Standard for quality specification of group-H gases

As far as position of Finnish gas market in EU is concerned, natural gas in Finland is delivered by Gazprom (Russia) at reference combustion temperature of 20 °C and the reference conditions for volume are 0 °C and 101.325 kPa. Quality-wise, it belongs to 2H group. The following Table 3 shows the representative gas composition in Finland, and Table 4 shows gas specifications for Finnish consumers.

Table 3 (Kimpton & Brown, 2010): Sample representing gas composition in Finland

Property/ Component	Unit	Value
Methane	%	> 98
Ethane and higher hydrocarbons	%	< 1
Nitrogen	%	< 1
Gross calorific value	MJ/m3	39.9
Net calorific value	MJ/m3	36.0
Wobbe Index	MJ/m3	53.0

The reference temperature for combustion is 20 °C and the reference conditions for volume are 0 °C and 101.325 kPa.

Table 4 (Kimpton & Brown, 2010): Gas composition by Finnish distribution company Gaasienergia AS for delivery to domestic consumers

Property/ Component	Unit	Range
Methane content	%	96.91 – 98.33
Gross calorific value	MJ/m^3	36.70 – 38.00
Net calorific value	MJ/m^3	32.70 – 34.00

The reference temperature for combustion is 20 °C and the reference conditions for volume are 0 °C and 101.325 kPa.

Finland, alongwith Baltic States Latvia, Lithuania and Estonia, is remote and thus unconnected with the rest of the European gas transmission system. These four countries get natural gas only from Russia; they are exempted from the EU regulation of complete unbundling of the gas market owing to the lack of competition.

2.4.4 Concerns over MN as Gas Quality Standard in Europe

There is a drive to specify methane number as gas quality parameter in Europe, and Euromot has specified an MN of minimum 80 for natural gas engines (Euromot, 2012). However, there are several reservations over incorporation of Methane Number in the joint EU natural gas standards for both combustion and non-combustion parameters (CEN Mandate M/400) under investigation by work group CEN/TC 234 WG 11. These concerns are expressed by organizations such as Gas Infrastructure Europe (GIE), an association representing the sole interest of the infrastructure industry in the natural gas business including Transmission System Operators (Gas Infrastructure Europe (GIE), 2012) and Norwegian Gassco (Wellinger, 2013). Main reasons behind this stance by Gas Infrastructure Europe (GIE) comprise the absence of a standard MN determination method, inconsistency of methane numbers calculated from various methods, not accounting for hydrogen and hydrocarbons heavier than butane, and minor impact (only 2%) on the current gas consumers in Europe as MN measure is mainly meant for emission and efficiency of gas fuelled reciprocating engines. The minimum limit of MN 80 proposed by Euromot would not only render most of the existing European gas uneconomical due to further gas processing and modification of current infrastructure but also does not guarantee to optimize the engine performance. (Gas Infrastructure Europe (GIE), 2012)

2.5 LNG Quality

Though main reason for LNG production is its transport flexibility (Stat Oil, 2010), yet the quality it contains emerges as key issue for energy economies. There are three (3) main analyses of the natural gas corresponding to 3 main stages in the LNG value chain, i.e.,

- at the well-head (gas field)
- at the liquefaction plant, the LNG which is loaded for transportation
- at the receiving terminal, the LNG which is sent for regasification

All these analyses tend to be rather different at each stage, that is, the LNG composition varies, even during the transportation and storage due to “weathering or aging” and “boil-off” production. Therefore, it is imperative to have the LNG contractual quality based on the one, obtained after regasification. A little work has been done in Europe on particularly LNG quality, for example LNG specifications implemented at Zeebrugge (Fluxys Belgium SA, 2013) and Gate Terminals (Hammerschmid, 2013) in Belgium and the Netherlands respectively, and in the UK; however, there is no precedence of any such effort for Finland up till now (as of 2013). Here, this area is un-explored due to, as one reason, limited contribution of natural gas in the country’s total primary energy.

2.6 Quality Adjustment of LNG

International trading of natural gas is increasing through growing LNG shipment and pipeline interconnectors. Offshore operations, pipeline integrity, and the safety and reliability of downstream gas-fired equipment can be compromised by variations in gas quality (Kidnay, et al., 2011).

The impact of LNG introduction proves to less challenging than that of rich, unprocessed gas into the domestic natural gas grid, except the last-end quality fluctuation issues owing to variations in timing and supply blending. The absence of potential for hydrocarbon liquid formation and fallout coupled with consistency of end use burner tip behavior should minimize operating cost and downtime concerns, however this involves substantial cost increases attributable to monitoring and manpower additions (Coyle, et al., 2007). Nonetheless, maintaining consistent quality features of the integrated gas stream while introducing vaporized LNG into system supplies is challenging since blending of the LNG stream with inert gases (e.g., nitrogen) is required to retain desirable flame and combustion characteristics.

As the LNG becomes a global stock, it requires being flexible in terms of its specifications in order to satisfy the target markets, which have largely diverse demands resulting considerable movement towards technical solutions for conditioning LNG on liquefaction and receiving ends (Carnell, et al., 2009).

To get an insight of the situation, Figure 2.6-1 displays heating value specifications for different countries. In one example a gas with HHV of 42.6 MJ/Sm^3 is suitable for the Japanese and Korean markets, but is too high for the US or UK. In the second example a gas with HHV of 37.2 MJ/Sm^3 meets US/UK specs but has an HHV excessively low for Korea or Japan. Both examples, however, are within the ranges allowed in France and Spain.

A variety of solutions exists both at liquefaction and receiving ends of LNG cargo in order to modify/ adjust the LNG quality according to market demand, so called Wobbe Quality Adaptation (WQA) (Gate Terminal B.V., 2013). However, the current study is limited to that at receiving-ends only. These methods mainly focus on changing the HHV of LNG by either reducing (de-richment) or increasing (enrichment) the Wobbe Index. As per existing practice, the following methods are in use for the purpose.

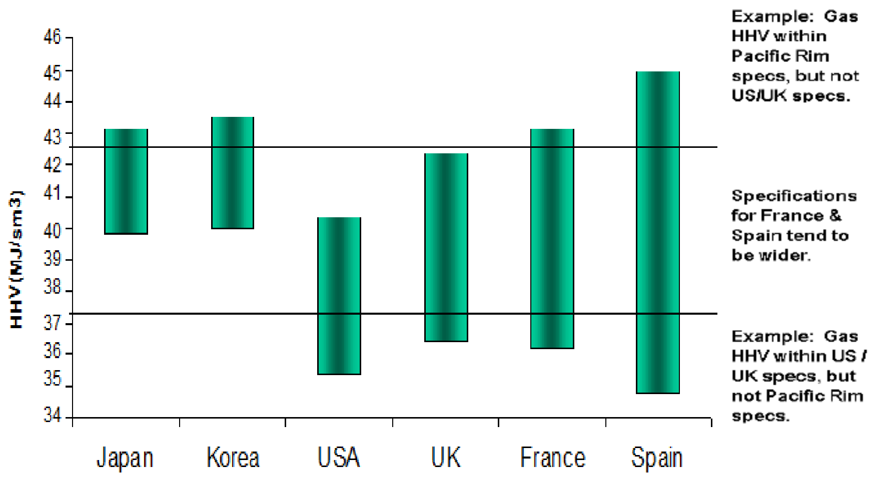

Figure 2.6-1 (Carnell, et al., 2009): Worldwide calorific value specifications

2.6.1 Heating Value Reduction (De-richment)

Numerous de-richment techniques are practised in the industry, including:

- LPG/ NGLs extraction
- Carbon dioxide ballasting
- Air ballasting
- Flue gas injection
- Hydrogen ballasting
- Nitrogen injection/ Nitrogen ballasting or dilution

Air and nitrogen ballasting are the most-used methods due to simple, economical processes (GL Noble Denton, Pöyry Management Consulting, 2011). Figure 2.6-2 shows typical arrangement of this process. At the receiving end, on-terminal ballasting installations are utilized to reduce Wobbe Index/ calorific value of the incoming LNG by injecting the liquid or gaseous nitrogen in the LNG flow. This method is practically applied at the Dutch LNG Terminal GATE in The Netherlands, as it offers its customers a range of Gross Calorific Value (GCV) 39.5 MJ/Nm^3 – 46.7 MJ/Nm^3 and a Wobbe index 49.9 MJ/Nm^3 and 57.24 MJ/Nm^3 natural gas, after unloading the imported LNG (Gate Terminal B.V., 2013). UK's Grain LNG terminal uses this method for incoming cargoes, so it is equipped with two Liquid Nitrogen Plants (owned and operated by Air Products) and four Air Separation Units with a storage capacity for 5000 tonnes of liquid nitrogen (National Grid, 2014).

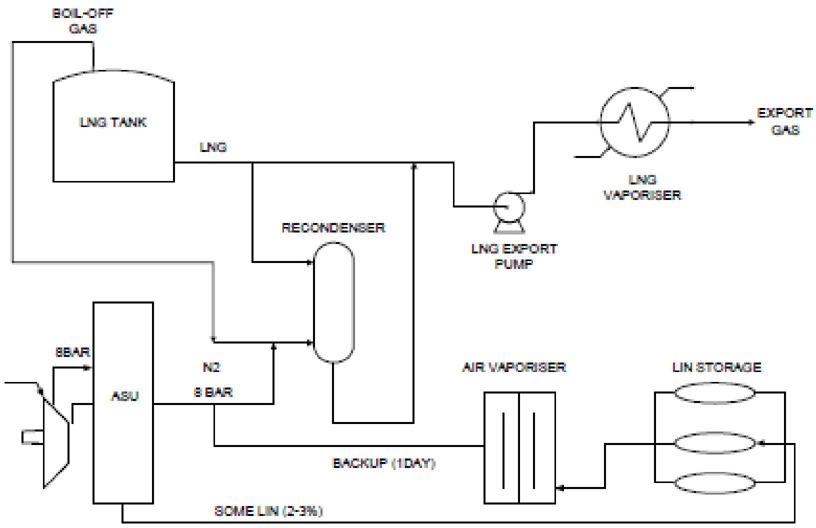

Figure 2.6-2 (GL Noble Denton, Pöyry Management Consulting, 2011): Nitrogen ballasting configuration at LNG receiving terminal

Ballasting with N_2 or CO_2 decreases the HV of natural gas, however, it casts a positive impact on the methane number of the blend, thereby reducing the NOx concentration, boosting the knock resistance and improving the knock-rating of the gaseous fuel. In addition, CO_2 mixing is twice more effective than that by N_2, shown in Figure 2.6-3. This phenomenon was studied on a natural gas SI engine customized to CHP operation. (Brecq, et al., 2003)

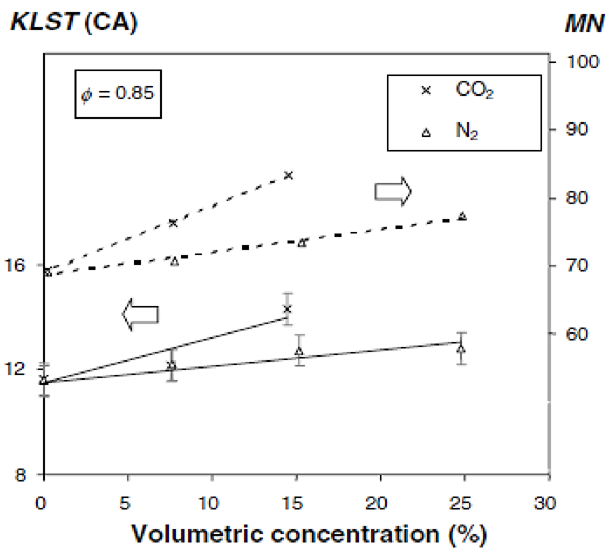

Figure 2.6-3 (Brecq, et al., 2003): Impact of inert gases addition on MN and KLST (knock limited spark timing) in degrees of crank angle

Addition of hydrogen in natural gas decreases the Wobbe index of mixture for up to 75% H_2 mixing in NG. Several studies examined the effect of hydrogen injection on thermodynamic and transport properties of natural gas. One such research (Schouten, et al., 2004) states that Wobbe actually decreases as long as H_2 injection goes beyond 75-80%. Figure 2.6-4 illustrates the relation of both parameters.

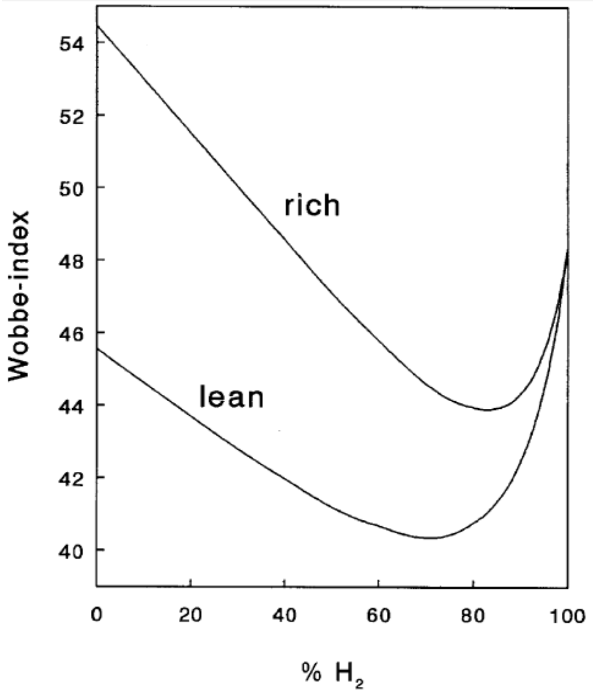

Figure 2.6-4 (Schouten, et al., 2004): The Wobbe index as a function of the hydrogen mole fraction for a rich and a lean gas

The potential benefits of H_2 injection in natural gas include reduced GHG emissions and air pollution. The current transmission pipeline system (< 138 bar) may be utilized for up to 50% H_2 injection in natural gas with small modification of pipeline integrity procedures to counter hydrogen induced cracking/ embrittlement, while lower H_2 concentration (5-15%) have negligible impacts as depicted in Figure 2.6-4. Since hydrogen has high permeation coefficient through most of high strength steels and elastomers, it is more susceptible to leakage at sufficiently high pressures (Dodds & Demoullin, 2013). Additionally, the gas metering may need to be recalibrated (< 4%) when measuring less than 50% hydrogen-natural gas blend. (Melaina, et al., 2013)

With all its pros and cons, H_2 injection or delivering only hydrogen gas as utility in the pipelines could be a cogent step on the pathway to decarbonization of hydrocarbon gases (Dodds & McDowall, 2013).

2.6.2 Heating Value Enhancement (Enrichment)

LNG enrichment is commonly carried out by

- LPG injection
- CO_2 removal
- Nitrogen removal

2.6.2.1 LPG Injection

The procedure, illustrated in Figure 2.6-5, is adopted typically on LNG receiving end only. This method, particularly propane injection, is in utilization at Zeebrugge LNG terminal at Belgium, and at Grain LNG terminal UK (National Grid, 2014).

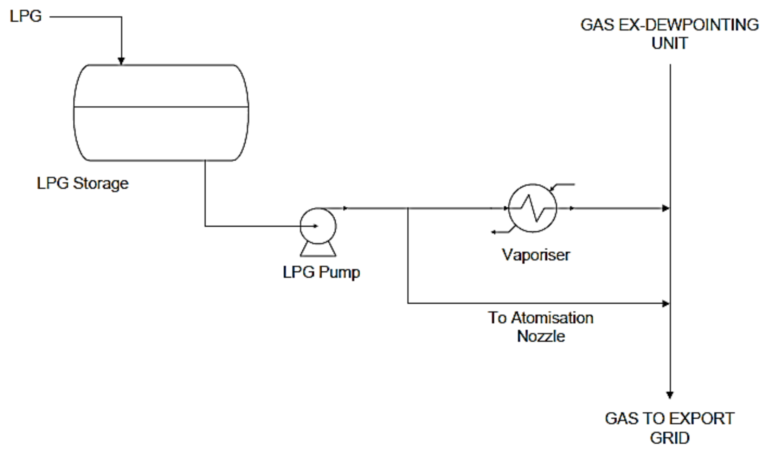

Figure 2.6-5 (GL Noble Denton, Pöyry Management Consulting, 2011): Schematic diagram of LPG injection

There are various methods to produce LPG, which is subsequently added to LNG (Katz & Lee, 1990), such as

- LPG Recycle
- Turbo-expander extraction
- Scrub Column Modifications or Front end LPG recovery

Similarly, CO_2 and nitrogen can be separated from natural gas through myriad of methods, (Kidnay, et al., 2011) including

- Membranes
- Pressure Swing Adsorption (PSA)
- De-oxygenation of Submerged Combustion Vaporizer flue gas using hydrogen
- Inert Gas Production by Combustion
- Cryogenic Fractionation

2.6.3 Other Techniques

Several other quality adjustment solutions are exercised as well to manipulate the properties of LNGs. Two such examples are described here.

- **Downstream Swaps**

  Gas flows of different qualities (from different sources) are mixed or swapped in order to obtain lean or rich gas as per requirement. For example in Belgium, rich natural gas is converted to lean gas (Slochteren gas) by nitrogen injection at Lillo and Loenhout stations to compensate the L-grid, while vice versa is also carried out by adding rich gas. Similarly, at Ville-sur-Haine and Warnant-Dreye stations rich gas is degraded by mixing lean gas. (Fluxys Belgium SA, 2013)

- **Mixed send-out (Blending)**

  In this method, LNGs of unlike qualities are combined to get the desired blend, but it is only possible if a number of storage tanks are available to store different qualities of LNGs. These qualities are then collectively vapourized in certain proportions to achieve the required specifications.

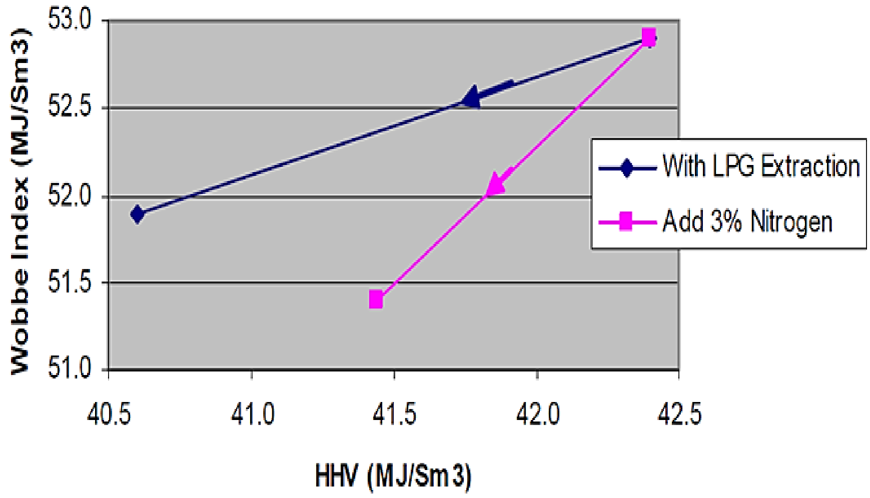

Figure 2.6-6 (Coyle, et al., 2007): Comparison of LPG extraction and Nitrogen injection

Adding 3% nitrogen (instead of extracting LPG) does not change heating value as much as LPG extraction (Figure 2.6-6) however, the nitrogen has a greater effect on Wobbe Index. Since Wobbe Index is often a more stringent requirement than heating value, increasing nitrogen content may be a feasible option to meet specifications in some cases. (Coyle, et al., 2007)

When considering using nitrogen on the liquefaction end to meet natural gas specs, it should be confirmed that the shipping and receiving end can take a high nitrogen LNG because the boil off gas from a 3 mol % nitrogen LNG contains over 50 mol %

nitrogen. Also, the receiving terminal might have to send out boil off gas that meets the pipeline specifications prior to recondensing in the LNG sendout. In general the nitrogen solution is handled at the receiving end. (Carnell, et al., 2009)

As regards the role of methane number in global LNG source selection, a gas application requiring a minimum MN (AVL) of 80 can use only 38% of global supply, while that doing a minimum MN (AVL) of 70 can use 90% of global supply, as described in Figure 2.6-7.

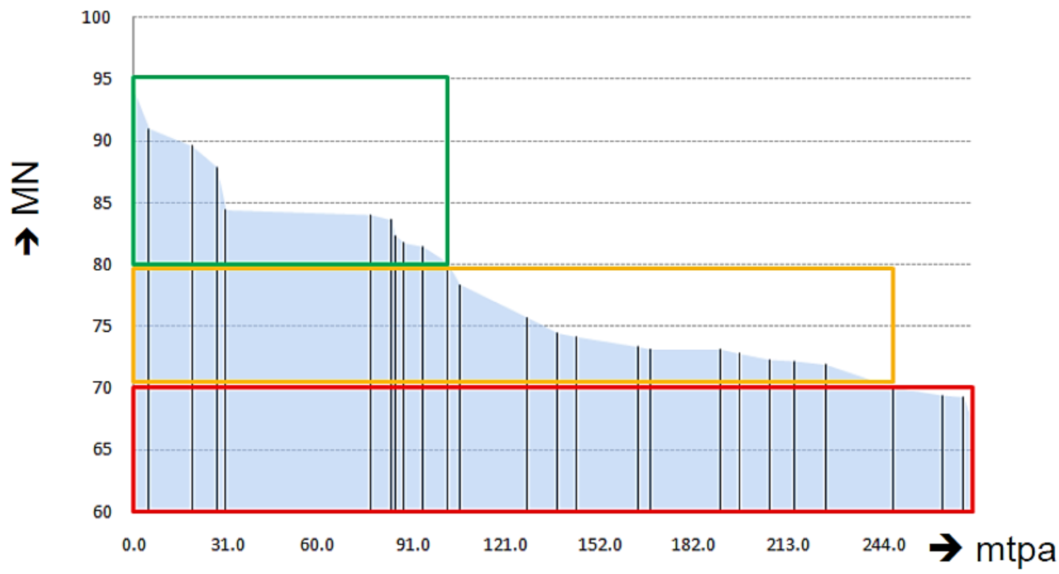

Figure 2.6-7 (MAN Diesel & Turbo, 2013): Relation of Methane Number and the LNG produced in the world

Since various nations are exploiting a wide range of global gas sources through the LNG imports, limit of gas qualities suitable to the grid would have to be augmented. Therefore, efforts are currently focused at finding cost-effective solutions to accept imported LNG into existing gas systems. Furthermore, diverse natural gases, such as landfill gas, biogas, mines gas, and even the hydrogen, would be the potential candidates to be adjusted within the current networks.

3. Natural Gas Specifications in Finland – Requirement and Availability

In order to define the suitable LNG quality for Finnish users, knowledge of the market requirement is essential element. This chapter incorporates the detailed demand-supply data of each natural gas sector in Finland as designated in Chapter 1, alongwith available LNG sources worldwide.

3.1 Calculation Standards

All the calculations performed in the study of this data are based on ISO 6976:1995 with Combustion reference conditions of 25°C, 1.01325 bara, and Volume-metering reference conditions of 0°C, 1.01325 bara. The calculations for the Heating Value, Wobbe and Compression Factor are on Dry, Real basis. The following equations have been utilized for computation of parameters (ISO, 1995).

$$Z_{mix}\,(t_2, p_2) = 1 - \left[\sum_{j=1}^{n} x_j\,\sqrt{b_j}\right]^2 \qquad \text{Eq. (3.1)}$$

$$\rho\,(t, p) = \frac{1}{Z_{mix}\,(t, p)}\left[\frac{p}{RT}\sum_{j=1}^{n} x_j M_j\right] \qquad \text{Eq. (3.2)}$$

$$d\,(t, p) = \frac{Z_{air}\,(t, p)}{Z_{mix}\,(t, p)}\sum_{j=1}^{n} x_j \times \frac{M_j}{M_{air}} \qquad \text{Eq. (3.3)}$$

$$\widetilde{H}[t_1, V(t_2, p_2)] = \frac{1}{Z_{mix}\,(t_2, p_2)}\sum_{j=1}^{n} x_j\,\widetilde{H}_j^{\circ}[t_1, V(t_2, p_2)] \qquad \text{Eq. (3.4)}$$

$$W[t_1, V(t_2, p_2)] = \frac{\widetilde{H}[t_1, V(t_2, p_2)]}{\sqrt{d(t_2, p_2)}} \qquad \text{Eq. (3.5)}$$

where

$Z_{mix}\,(t_2, p_2)$ is the compression factor of the gas at the metering reference conditions

x_j is the mole fraction of component *j*

$\sqrt{b_j}$ is the summation factor of component *j*

$\rho\ (t,p)$ is the density of real gas

M_j is the molar mass of component j

M_{air} is the molar mass of dry air of standard composition

p is absolute pressure

R is the molar gas constant (=8.314510 J.mol^{-1}. K^{-1})

t is temperature in Celsius

T is the absolute temperature

$d\ (t,p)$ is the relative density of the real gas

$Z_{air}\ (t,p)$ is the compression factor of dry air of standard composition

$\widetilde{H}[t_1, V(t_2,p_2)]$is the real-gas calorific value on volumetric basis

$\widetilde{H}_j^{\circ}[t_1, V(t_2,p_2)]$is the ideal calorific value on a volumetric basis of component j

W is Wobbe index of the real gas

Subscripts

1 is for the combustion reference conditions

2 is for the volumetric or metering reference conditions

$$\rho = \rho\ (T_2, p_2) \times \left[\frac{101.325\ T_2}{288.15\ p_2}\right] \times \frac{[1 + 0.000025\ (T_2 - 288.15)]}{[1 + 0.000020\ (p_2 - 101.325)]} \qquad \text{Eq. (3.6)}$$

$$d = d\ (T_2, p_2) \times \frac{[1 + 0.000014\ (T_2 - 288.15)]}{[1 + 0.000020\ (p_2 - 101.325)]} \qquad \text{Eq. (3.7)}$$

$$\widetilde{H}_I = \widetilde{H}_I\ (T_1, T_2, p_1, p_2) \times \left[\frac{101.325\ T_2}{288.15\ p_2}\right] \times [1 + 0.00010\ (T_1 - 288.15)] \times \frac{[1 + 0.000025\ (T_2 - 288.15)]}{[1 + 0.000020\ (p_2 - 101.325)]} \qquad \text{Eq. (3.8)}$$

$$\widetilde{H}_S = \widetilde{H}_S\ (T_1, T_2, p_1, p_2) \times \left[\frac{101.325\ T_2}{288.15\ p_2}\right] \times [1 + 0.00010\ (T_1 - 288.15)] \times \frac{[1 + 0.000025\ (T_2 - 288.15)]}{[1 + 0.000020\ (p_2 - 101.325)]} \qquad \text{Eq. (3.9)}$$

$$W = W\,(T_1, T_2, p_1, p_2) \times \left[\frac{101.325\,T_2}{288.15\,p_2}\right] \times [1 + 0.00010\,(T_1 - 288.15)] \times \left\{\frac{[1 + 0.000020\,(p_2 - 101.325)]}{[1 + 0.000036\,(T_2 - 288.15)]}\right\}^{-\frac{1}{2}} \qquad \text{Eq. (3.10)}$$

The data values following the other codes or standards have been converted to conditions of this study, using ISO 13443:1996 as per the relations given hereunder (ISO, 1996).

where

$\widetilde{H}_I$ is volume-based inferior calorific value (LHV)
$\widetilde{H}_S$ is volume-based superior calorific value (HHV)

Simple letters represent ISO reference conditions (15°C, 15°C, 101.325 kPa) and those with (T_1, T_2, p_1, p_2) represent conditions other than the ISO, for example W is Wobbe index at ISO reference conditions (15°C, 15°C, 101.325 kPa) and $W\,(T_1, T_2, p_1, p_2)$ is Wobbe index at conditions (T_1, T_2, p_1, p_2)

In addition, the ideal and real heating values have been taken as numerically equal, since the real gas heating value varies from the ideal heating value by approximately 0.005% at ISO-conditions (ISO, 1995) [and < 0.01% at ASTM D3588-conditions (ASTM D3588 - 98, 1998)] which is practically negligible and comes within accuracy limits of heating values. As such, unlike the contextual concept of ideal-real, dividing the ideal heating value by compressibility factor (or compression factor) does not give the real heating value but rather it gives ideal heating value per real cubic meter. In fact, computing real heating value from ideal heating value involves calculation of a correction factor (called enthalpic correction factor) which is very small for typical natural gas mixtures. All the calculation and compositional analysis has been carried out in dry basis in line with ISO 6976:1995, unless otherwise stated.

3.2 Natural Gas Quality Demand

The market of natural gas in Finland is divided into broad categories representing the major consumer classes. The nominated application areas in the consumption market of Natural Gas in Finland comprise traffic, industry and national gas grid, which were further explored to identify the market demand.

3.2.1 Traffic Applications

Natural gas is used as fuel in shipping and land traffic. Therefore, traffic applications are classified into two sub-categories, marine and on-shore/land traffic.

3.2.1.1 Marine Traffic/ Engines

Accordingly, the information was collected from the following marine engine manufacturers/ suppliers and tabulated in Table 5.

- Wärtsilä
- MAN
- Caterpillar
- Rolls-Royce Marine
- GE

Wärtsilä engines are optimized for full power output against a minimum MN 80, otherwise the efficiency is lowered for which different measures are adopted, for example,

- Tuning is possible to some extent.
- Reduction of compression ratio of the engine.
- De-rating the engine to a lower power output.

Consideration of MN variation is important at this stage.

MAN Diesel&Turbo have some marine engine models which can run on methane number as low as 60, whereas here MN 80 is taken which is a stringent measure for their certain engine range. They also have computation tool to calculate MN. (MAN Diesel & Turbo, 2013)

The operation of Caterpillar Marine engines is also possible on natural gas with minimum methane number of 55 but at reduced load (Caterpillar Marine Power Systems, 2012).

Table 5: Fuel gas specifications of marine engines

Property/ Component	Unit	Range					
		Wärtsilä[a]	MAN[b]	Caterpillar[c]	Rolls-Royce[d]	GE[e]	A new customer/ ship owner[f]
Methane Number		≥ 80	≥ 80	≥ 80	≥ 70	59.44	≥ 80
Lower Heating Value	MJ/Nm³	≥ 28	≥ 32.4	≥ 28	≥ 36	33.955	≥ 28
Lowe Wobbe index	MJ/Nm³	47.825					
Modified Wobbe Index						40 – 60	
Sulphur (as H_2S)	mg/m³		5	≤ 770, ≤ 20	76		0
Total sulphur	mg/m³		30				
Methane (CH_4)	vol%					50-100	≥ 70
Ethane (C2+)	vol%					≤ 30	
Hydrogen (H_2)	vol%					≤ 5	0
Ammonia (NH_3)	mg/m³			≤ 25			0
Fluorines + Chlorine	mg/m³		5 + 10	≤ 50			0
Diolefins (i.e., butadiene, propadiene)						0	
Oil content	mg/m³			≤ 50			
Particulate matter	mg/m³		50	≤ 50	≤ 50	≤ 30 ppmw	≤ 50 mg/kg
Particulate matter size	micron		10	≤ 5	≤ 5	≤ 5	≤ 5
Tar content	mg/m³			≤ 10			
Silicium/ Siloxanes	mg/m³			≤ 10		≤ 50 ppbw	
Water				0	0	0	0
Condensate				0	0	0	

[a] Dual-Fuel Marine Engines, IMO Tier III-compliant when operated on Natural Gas mode (Wärtsilä Corporation, 2010) (Krooks & Melamies, 2013)

[b] (MAN Diesel & Turbo SE, 2013) (MAN Diesel & Turbo, 2013)

[c] Preliminary performance data for Caterpillar Dual Fuel Engine M46DF (Pon-Cat, Pon Equipment B.V., The Netherlands, 2013) (Caterpillar Marine Power Systems, 2012)

[d] (Rolls-Royce Marine AS, 2012) (Rolls-Royce Marine AS, 2013)

[e] (Glotain, 2014) (GE Energy, 2009)

[f] (Mattila, 2013)

Rolls-Royce marine specs are taken from their brand RR Bergen. The marine gas engine ratings for Rolls-Royce *RR Bergen B35:40V,* lean-burn gas marine engine, conform to ISO 3046-1, at maximum 45°C ambient air temperature and maximum 32°C sea water temperature.

GE is active share holder of gas turbine market in Finland. The fuel composition limits for Dry Low Emission (DLE) combustion system has been considered for their brand *AeroDerivative* Gas Turbines. The turbines can work for natural gas of LHV 800-1200 btu/scf (30-45 MJ/m^3). Premixed combustion is utilized in DLE turbines and gas constituent limits are stricter than those for other models; furthermore, these are equipped with emission reduction system in order to cope with European emission regulations. Their models LM2500, LM6000 and LMS100 are typically used in small power generation (25 to 100MW) and for marine applications (LM2500).

3.2.1.2 Land Traffic

Natural gas is utilized as a vehicle fuel in gaseous (CNG) or liquid phase (LNG). LNG can be used as such or as CNG for both heavy-duty vehicles (HDVs) and cars. This is to be noted that engines of current light duty vehicles operate at stoichiometric ratios with closed loop control and 3-way catalysts and hence are capable to use fuel of any (wide margin) MN fuel, since variation in fuel composition is immediately compensated by engine control system (Eaves, 2010).

For on-shore/ land traffic, data, listed in Table 6, was gathered from these manufacturers.

- Volvo
- IVECO
- Cummins
- Scania
- Mercedes-Benz

Table 6: Fuel gas specifications for land-traffic engines

Property/ Component	Unit	Range				
		Volvo[a]	IVECO[b]	Cummins[c]	Scania[d]	Mercedes-Benz[e]
Methane Number		> 83	> 70	65 – 80	≥ 70	≥ 70
Methane	mol%	> 92	> 83	≥ 90	> 70	≥ 80
NMHC	mol%		< 13			
Ethane	mol%	< 3		≤ 4		≤ 12
Ethane+ (C2+)						≤ 8.5
Propane	mol%	< 2		≤ 1.7		≤ 6
Butane	mol%					≤ 2
Butane and higher (C4+)	mol%	< 0.5		≤ 0.7		
Pentane						≤ 1
C6+						≤ 0.5
CO_2	mol%		< 14		< 3	
N_2	mol%		< 14			
$N_2 + CO_2$	mol%	< 6		≤ 3		≤ 15
Water	mg/Nm³		< 55	0	< 30	≤ 40
H_2	vol%		< 5	≤ 0.1		≤ 2
CO	vol%			≤ 0.1		
O_2	vol%			≤ 0.5	< 3	≤ 3
H_2S	ppmv	< 3	< 10		< 5 mg/m³	≤ 7 mg/m³
Mercaptan sulphur	mg/m³				< 15	≤ 8
Total sulphur	mg/Nm³	< 15 ppmv	≤ 10	≤ 0.001 wt.%	< 120	≤ 10
Siloxanes	mg/Nm³		< 5			
Particulate matter size	micron	< 1				
Oil content				0		
Lower Heating Value	MJ/Nm3	37.451-40.708		30.828-43.403		≥ 37.49
Lower Wobbe Index	MJ/Nm³	47.11 – 51.44		46.67-49.43		
Density	kg/Nm³					0.72-0.91
Higher Heating Value	MJ/Nm³				30-45	
Gross Wobbe Index	MJ/Nm³				46.1-56.5	

[a] Fuel gas specifications of Volvo truck engine (Raatikainen, 2013)

[b] Fuel gas specification of IVECO truck engine (Havia, 2013)

[c] Natural gas fuel for Cummins engines (Adam, 2013) (Cummins Power Generation, Inc., 2012) based on average molecular weight from Standard Handbook of Petroleum and Natural Gas Engineering (Lyons, 1996).

[d] (Pettinen, 2013) (Scania CV AB, 2013) (Strömberg, 2013) (NGVA Europe, 2013) (Svensson, 2011)

[e] Tested with G20-G25 Reference Gases (CEN, 2003) (Eskelinen, 2013) (Graf, et al., 2009) (INGAS, 2009)

Volvo uses CARB methane number method which returns around 7.9% higher MN values than the AVL method used in this study (Southern California Gas Company, 2005). So AVL MN 83 (rounded off from 82.89) is taken equivalent to the CARB 90 MN to synchronize with other methane numbers in the data. Although Volvo also quotes MN 85 calculated by their own software "MN85" (MN85 is a Volvo name for the specific software setting in the gas system to adjust for gas with methane number 85), yet it is not clear which algorithm it uses. In addition, they specify variation limit of +/-2 for stoichiometric air fuel ratio (SAFR) and heating value (HV) indices for Volvo LNG truck, *MethaneDiesel*, which are computed by their spreadsheet, a Microsoft® Excel calculator. (Raatikainen, 2013)

IVECO defines its metering conditions at 298.15 K (assumed), 293.2 K and 101.3 kPa, so the affected combustion and non-combustion parameters, such as LHV, HHV, WI, density, relative density and compression factor, were changed to ISO 6976:1995 reference (used in this thesis) combustion and metering conditions i.e., 25°C, 0°C, 101.325 kPa by using ISO 13443:1996.

The natural gas composition provided by Cummins engines is governed by CES (Cummins Engineering Standard) 20067. The real Wobbe Index, HHV and LHV for Cummins are as per ASTM D3588 conditions of 60°F (15.6°C) and 14.696 psia. Density and relative density were calculated by Equations 3.11 and 3.12 (ASTM D3588 - 98, 1998).

$$\rho = \frac{p}{RT}\sum_{j=1}^{n} x_j M_j \qquad \text{Eq. (3.11)}$$

$$d = \sum_{j=1}^{n} x_j d_j = \sum x_j \frac{M_j}{M_{air}} \qquad \text{Eq. (3.12)}$$

(where the all the notations are as given in Section-3.1)

Values were converted to SI units which subsequently, through ISO 13443:1996, were first shifted to ISO reference conditions (15°C, 15°C, 101.325 kPa) by means of Equations 3.6-3.10, and then to the standard conditions of this study calculations (25°C, 0°C, 101.325 kPa, real dry gas) as per ISO 6976:1995 in order to synchronize the specs for comparison.

Scania uses natural gas conforming to ISO/DIS 15403 class-H natural gas composition. The metering reference conditions are defined at 273.15 K and 101.325 kPa (Scania CV AB, 2013).

Daimler AG, the makers of Mercedes-Benz vehicles seek compliance of German standard DIN 51624:2008-02, "Automotive fuels - Compressed natural gas - Requirements and test methods" (Beuth Verlag GmbH, 2008), which is basically a standard for CNG as automotive fuel. For Mercedes-Benz vehicle engines (particularly passenger cars), CO_2-tests are conducted with EN 437 Reference Gas G20 whereas those for CO, NOx and HCs are carried out with G25. (Eskelinen, 2013)

The fuels for homologation of light and heavy-duty vehicle engines are selected such that engine could maintain its emissions and efficiency on the gaseous fuels available in European market. The two types of gases (H & L) in Europe vary in their HV, Wobbe Index and also λ-shift factor. H- and L-gases have λ-shift factor ranges 0.89-1.08 and 1.08-1.19 respectively (UNECE, 2013). The reference fuels used for vehicle testing show the extreme variation of λ-shift factor (the lambda shift factor shows the change in air/fuel ratio when an engine is operated on pure methane and then on other fuel gas). Currently, two main standards govern the certification or homologation of natural gas vehicles (NGVs); these are UNECE R83 and UNECE R49 Regulations developed by United Nations Economic Commission for Europe

(UNECE). The former outlines the emission limits for the Light-Duty Vehicle fuels including NGVs by defining reference fuel gas specifications for testing, whereas the latter administers the same task for Heavy-Duty Vehicles along with describing the procedure for type-allocation to them (UNECE, 2011).

As per UNECE NGV classification standard, the extreme reference fuels for H-range are EN 437 defined gases, GR and G23, while those for L-range are G23 and G25 (UNECE, 2012). Commonly, heavy-duty vehicles are approved for all fuel ranges (universal) by testing against GR and G25, while they can also opt for either H-, L- or both. Light vehicles on the other hand are tested against G25 and G20 for full available gases' range (NSCA, 2006). The composition of test gases as specified in Annexure 10A of R83 Rev.4, and Annexure 6 of R49 Ammend-1, is given here in Table 7.

Table 7 (UNECE, 2013) (CEN, 2003) (UNECE, 2013) (NGVA Europe, 2013) : Light and Heavy Duty Vehicle reference fuels for standardizing vehicle emissions

Component	Unit	GR	G23	G25	G20
Methane	mol %	87 ± 2	92.5 ± 1	86 ± 2	99 ± 1
Ethane	mol %	13 ± 2	-	-	-
Balance (inerts + C_{2+})	mol %	≤ 1	≤ 1	≤ 1	≤ 1
N_2	mol %	-	7.5 ± 1	14 ± 2	-
Sulfur	mg/m^3	≤ 10	≤ 10	≤ 10	≤ 10
Methane Number		70-78	82-85	70-76	95-100

In the nutshell, G20 and G25 are regulation-R83 Light-duty reference fuels, while GR, G23 and G25 serve as the current regulation-R49 Heavy-duty reference fuels (Bruijstens, et al., 2008). Therefore, the properties of these gases would establish framework of fuel gases for land transport sector, which are graphically plotted against other available specifications given by vehicle manufacturers.

3.2.2 Off-grid Industrial Applications

The industrial users typically comprise CHP (Cogen)/ Power Plants (gas turnbines), and industries which utilize natural gas as a fuel and for chemical synthesis. Such industries include pulp and paper, metal, food, packaging, bio and forest product, pharmaceutical and leather. LNG can replace fuel oil and LPG in these industries. Three groups were constituted for this category, with gen-sets, gas turbines in one group and burners, boilers in the second, and potential general industry customers in the third group.

3.2.2.1 Power Production, Gen-sets, Gas Turbines

Following companies were consulted for natural gas specifications for their gen-sets and gas turbines, and their data is incorporated in Table 8:

- Wärtsilä
- Cummins Power Generation
- MAN Diesel & Turbo
- Hyundai
- MWM
- Rolls-Royce Power
- GE Energy
- GE Jenbacher

In Wärtsilä engines, the required gas feed pressure depends on the LHV, for instance, in SG and DF engines 28 MJ/Nm^3 needs 6 bara pressure for full engine output. However, in GD engines low LHV can be compensated with fuel sharing. SG and DF engine outputs depend on the Methane Number. Full engine output at highest efficiency is achieved at MN80; lower MN can be used with an influence on engine performance and may cause de-rating of the engine. GD engines are not affected by MN. The MN is calculated by Wärtsilä. Additionally, OEM offers customized solutions for the fuel gases with more than 3% hydrogen content or less than 70% methane contents. Also, the dew point of natural gas is below the minimum operating temperature and pressure, and volume calculation (Nm^3) is at 0°C and 101.3 kPa. (Wärtsilä Coporation, 2013)

Table 8: Fuel gas specifications for power gen-sets, gas turbines

Property/ Component	Unit	Range							
		Wärtsilä[a]	Cummins Power[b]	MAN[c]	Hyundai[d]	MWM[e]	Rolls-Royce Power[f]	GE Energy[g]	GE Jenbacher[h]
Methane Number		≥ 80	≥ 75	80 – 84	≥ 80	≥ 70	≥ 70	59.44	80
Lower Heating Value	MJ/Nm³	≥ 28	≥ 36	≥ 28	≥ 36	18	18-36	33.955	36
Methane (CH_4)	vol%	≥ 70	≥ 85				> 50	50-100	
Ethane (C_2+)	vol%							≤ 24	
Wobbe Index (lower)	MJ/Nm³		41.999						
Modified Wobbe Index								40 – 60	
Oxygen (O_2)	vol%								< 3
Sulphur (as H_2S)	vol%	≤ 0.05					50 ppm	< 20 ppmv	
Total sulphur including that from H_2S	mg/m³$_{CH4}$		≤ 30						< 50 mg/10kWh
Hydrogen (H_2)	vol%	≤ 3	≤ 3					≤ 5	
Ammonia (NH_3)	mg/m³$_{CH4}$	≤ 25	≤ 1						< 50 mg/10kWh
Halogens (Fluorines + Chlorines)	mg/m³$_{CH4}$	≤ 50	≤ 1 (Cl+2*Fl mg)						< 20 mg/10kWh**
Diolefins (i.e., butadiene, propadiene)								0	
Oil content	mg/m³$_{CH4}$		≤ 5				0	0	< 5 mg/10kWh
Particulate matter	mg/m³$_{CH4}$	≤ 50	≤ 30				≤ 50 mg/Nm³	≤ 30 ppmw	
Particulate matter size	micron	≤ 5	≤ 5				≤ 5	≤ 5	< 3
Total silicon content (Siloxanes)	mg/m³$_{CH4}$		≤ 1					≤ 50 ppbw	< 0.02*
Water	vol%	0					0	0	< 0.2
HC condensate	ppmv	0	≤ 20				0	0	0
Total trace elements/ impurities									< 350 g/m³ of catalytic converter
Density	kg/m³		0.7 – 1.2						
Relative density	-		0.735						
Relative humidity	%		80% no droplets						< 50
Dew point	°C								< 18

All the values of trace elements in GE Jenbacher are based on a fuel gas energy amount/content of 10kWh/m³.

* Si-content is calculated by formula

$$Si = \frac{\Delta\, Si_{content\ in\ engine\ oil}[ppm] \times OIl\ capacity\ [l]}{Average\ enigne\ power\ output\ [kW] \times \Delta\ Oil\ service\ life\ [h]} \times 1.1$$

** Total Chlorine + 2 (Total Fluorine)

[a] (Wärtsilä Coporation, 2013) (Krooks & Melamies, 2013) (Paulaharju, 2013)

[b] (Nurmi, 2013) (Cummins Power Generation Inc., 2009)

[c] ManDiesel gen-set Four-stroke gas engine (MAN Diesel & Turbo, 2007)

[d] (Hyundai Engine & Machinery Div., 2013)

[e] (MWM, 2013)

[f] (Backlund, 2013) (Rolls-Royce Marine AS, 2013)

[g] (Glotain, 2014) (GE Energy, 2009)

[h] (Bärlund, 2014) (GE Jenbacher GmbH & Co OG, 2012)

Cummins Power Generation calculates MN by AVL method by means of AVL 3.2 software programme with diluent gases removed. Some assumptions have been made in the composition of natural gas.

In GE Oil & Gas as well as in the gas turbine industry, it is a common practice to utilize the LHV when calculating the overall cycle thermal efficiency. While gas turbines can operate with gases having a very wide range of heating values, the amount of variation that a single specific fuel system can accommodate is much less. Variation in heating value as it affects gas turbine operation is expressed in a term known as modified Wobbe. This term is a measurement of volumetric energy and is calculated using the Lower Heating Value (LHV) of the fuel, specific gravity of the fuel with respect to air at ISO conditions, and the fuel temperature, as delivered to the gas turbine. The allowable modified Wobbe Index range between 40 and 60 is established to ensure that required fuel nozzle pressure ratios be maintained during all combustion/turbine modes of operation for standard fuel system configurations. The fuel gas specifications furnished here are for GE aero-derivative DLE (dry low emissions) gas turbines; limitations are more stringent for DLE combustion systems where "premixed" combustion is utilized. Larger gas turbines tend to have more "tolerant" fuel gas specifications than the smaller ones. (GE Energy, 2009)

GE Jenbacher engines are able to cover vast range of compositions (natural gas, coal mine gas, biogas or any special gas) and methane numbers right from 40 (for Associated Petroleum Gases) to 140 (high CO_2/ inert content natural gas) but the best engine efficiency is for MN around 90 (Bärlund, 2014).

3.2.2.2 Combustion Systems/ Burners, Boilers

Burning or combustion comprises one of wide usages of natural gas; the manufacturers of industrial burner systems, combustors and boilers, contacted for data (compiled in Table 9) include the following:

- Oilon
- Calortec
- IET Energy
- Bosch
- Clayton
- Fulton
- Weishaupt

Oilon Oy. are major burner manufacturers for Finnish market, selling combustion system of in 10 kW-80 kw capacity range for many applications, such as power plants, incinerators, CHP, and marine & industrial boilers, using variety of fuels (Oilon Oy., 2013). Their main concern regarding the fuel is its dryness, sulphur limits for the nozzle degradation according to valve supplier requirement, the heat value and energy density; they can operate in wide Wobbe window and accommodate hydrogen in the fuel before the melting of diffuser disc in the burner. For less than 6 t/h capacity basic auxiliary boiler, burner control system is barely sensitive to the changes in gas composition. For extraordinary change in composition, oxygen-trim needs to be adjusted. In any case, the flue gas adjustment has to be carried out for burners whenever there is change in fuel gas type. (Kurikka, 2013)

Enviroburners Ltd. are Finnish designers and manufacturers of industrial burners (system) up to 70 MW burners for power production and diverse industry. They use 13 kW – 32 MW range LNG burners by Max Weishaupt GmbH Germany (Lehtovirta, 2014), which is leading European brand of oil/gas/dual-fuel burners, heat pumps, heating systems and solar energy systems. The fuel natural gas specifications furnished by them date back to 2002, where they give limits for E-, LL- and air-natural gas mixture.

Table 9: Fuel gas specifications for industrial burners and boilers

Property/ Component	Unit	Range							
		Oilon[a]	Calortec[b]	IET Energy[c]	Bosch, Clayton, Fulton[d]		Weishaupt[e]		
					L-gas	H-gas	E-gas	LL-gas	LL+ air [#]
Methane Number				> 80	91.30	83.70	81.55	91.3	90.69
Lower Heating Value	MJ/Nm^3	25-40	>25	> 18	31.80	36	37.26	31.77	19.94
Higher Heating Value	MJ/Nm^3						41.26	35.21	22.10
Methane (CH_4)	vol%				81.8	92.3	93	81.8	51.4
Ethane (C_2H_6)	vol%				2.8	2	3	2.8	1.7
Propane (C_3H_8)	vol%				0.4	1	1.3	0.4	0.3
Butane (C_4H_{10})	vol%				0.2	0.6	0.6	0.2	0.1
Wobbe Index (lower)	MJ/Nm^3	38 – 60	>38		39.719	46.245	47.85	39.68	22.68
Gross Wobbe Index	MJ/Nm^3						52.99	43.97	25.14
Carbon dioxide (CO_2)	vol%				0.8-11.8	1-12	1-11.94	0.8-11.67	0.5-11.67
Nitrogen (N_2)	vol%				14	3.1	1.1	14	38.2
Oxygen (O_2)	vol%				0	0	0	0	7.8
Carbon monoxide (CO)	vol%				0	0	0	0	0
Sulphur (as H_2S)	vol%	≤ 0.1		< 200 ppm					
Total sulphur including that from H_2S	mg/m^3			< 2000					
Hydrogen (H_2)	vol%	< 10			0	0	0	0	0
Ammonia (NH_3)	mg/m^3_{CH4}			< 50					
Chlorine content	mg/m^3_{CH4}			< 100					
Fluorine content	mg/m^3_{CH4}			< 50					
Halogens (Fluorines + Chlorines)	mg/m^3_{CH4}			< 100					
Oil content	mg/m^3_{CH4}			< 400					
Particulate matter	mg/m^3_{CH4}			< 10					
Particulate matter size	micron			< 5					
Total silicon content (Siloxanes)	mg/m^3_{CH4}			< 5					
Density	kg/m^3				0.829	0.784	0.784	0.829	1
Relative density	-				0.641	0.606	0.606	0.641	0.773
Relative humidity	%	< 60	< 60	< 60					
Dew point	°C	< -10	< -10		58[&]	58[&]	57.8[&]	53.1[&]	57.6[&]

Gas 62.8% / Air 37.2%
[&] Flue gas dew point (combustion air dry)

[a] (Kurikka, 2013) (Karl Dungs GmbH & Co. KG, 2004)

[b] (Helpio, 2014) (Karl Dungs GmbH & Co. KG, 2004)

[c] (Bärlund, 2014) (Köllner, 2010)

[d] (Bärlund, 2014)

[e] (Lehtovirta, 2014) (Max Weishaupt GmbH, 2002)

Similar to other burner manufacturers, Weishaupt design burner according to any demanded fuel; Figure 3.2-1 displays their WM-G20 type gas burner. (Lehtovirta, 2014)

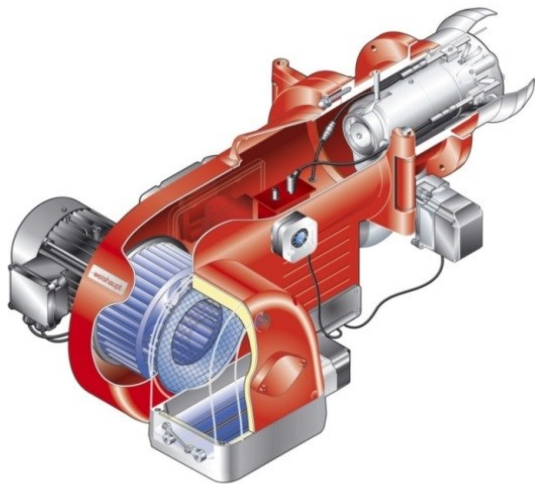

Figure 3.2-1 (Weishaupt, 2012): Cut-away drawing of a Weishaupt WM-G20 gas burner

Since no standard of natural gas quality has yet been finalized at national and European scale, Weishaupt burners accept +/- 2% variance in Wobbe Number of fuel natural gas, until there are no results from study/working groups of European standard. (Lehtovirta, 2014)

Calortec Oy. are Finnish producers of oil, gas and biofuel fired boilers, district heating plants, heat exchanger sub-stations for local and Russian market (Calortec Oy., 2013). They use Gasum grid gas, and burners from *Oilon, Weishaupt, Riello, Saacke* (Helpio, 2014), so their requirement matches burner suppliers.

IET Energy GmbH are Austrian developers of gas-powered CHP in 30-400 kW of electrical power range, as well as CHP container-modules of upto 2,000 kW (using various engine brands), gen-sets, direct drives, standby power plants and CHP switchboards (IET Energy GmbH, 2010). IET gas engine controllers can also be installed to other renowned gas engine makes (e.g., MAN, MWM, Jenbacher, Caterpillar, Perkins). In Finland, the application of IET on smaller engine range in the product portfolio is based on MAN engines and data for the same is available with Höyrytys Oy., the Finnish IET partner.

Along with Bosch Thermotechnik GmbH (the Thermotechology division/subsidiary of German Robert Bosch GmbH), both Fulton and Clayton are USA-based steam boilers and steam generator manufacturers having their products occupying a vast portion of Finnish market. Bosch has wide range of heating solution, such as CHP plants, shell boilers, water tube boilers and heat pumps (Bosch Thermotechnik GmbH, 2013). Fulton produces industrial and commercial scale heat-transfer systems with hot water (hydronic) and steam boilers, hot-oil heaters and temperature control equipment (Fulton Boiler Works, Inc., 2014). Clayton offers both fired boilers and unfired waste heat boilers in 245 to 9,810 kW range for steam rate of 391 to 15,650 kg/hr in free or skid-mounted configuration with feed-water treatment system (Clayton Industries, 2012). Products of all the above three companies are capable to use numerous fuels including oil, propane, LPG and natural gas. Data was obtained from Höyrytys Oy., the dealers of these brands in Finland, for small and medium-scale industrial boilers. The specifications contain natural gas of L-type (mainly for Eastern Europe) and H-type. The technical sheet mentions that all values are referenced to a nominal standard, but no further detail is available.

In Finland, combustion equipment, such as boilers and burners, are CE-marked to be used commonly G20 gas, while some of them are compatible to be used with LPG, propane i.e. G31 reference gas (Mielonen, 2013).

The industry which is already connected with Gasum grid, especially which use natural gas for heating/ combustion purposes, have their burners manufactured and calibrated to suit the grid (i.e., Russian supply).

3.2.2.3 Potential LNG Industrial Customers

LNG quality for potential industrial customers is represented by following Table 10.

Table 10 (Gasum Oy., 2013): Specifications of Gasum LNG and potential industrial customers

Property/ Component	Unit	Range			
		Gasum LNG Porvoo 2013*			Rautaruukki; Outokumpu
		Min.	Max.	Avg.	
Methane Number				97.40	
Lower Heating Value	MJ/Nm^3	34.992	36.211	35.829	36.2 – 39.6
Lower Wobbe Index	MJ/Nm^3	46.698	48.325	47.815	
Higher Heating Value	MJ/Nm^3	38.822	40.171	39.751	40 – 44
Gross Wobbe Index	MJ/Nm^3	51.553	53.658	53.059	53.2 – 55.3
Density	kg/m^3	0.722	0.739	0.726	420 – 465**
Methane	mol%	96.792	99.287	98.615	≥ 90
Ethane	mol%	0.123	1.520	0.592	≤ 7
Propane	mol%	0	0.372	0.035	≤ 3
n-Butane + i-Butane	mol%	0 + 0	0 + 0.006	0 + 0.059	≤ 1
n-Pentane + i-Pentane	mol%	0 + 0	0 + 0.012	0 + 0	≤ 0.03
Hexane	mol%	0	0.010	0	≤ 0.0015
Nitrogen	mol%	0.117	2.103	0.752	≤ 0.75
Carbon dioxide	mol%	0	0.004	0	≤ 0.01
Total sulphur	mg/m^3				≤ 7.3
Molecular weight	g/mol	16.144	16.533	16.228	

* Average composition for year 2013 (1.1.2013 to 30.11.2013) at reference conditions 25°C (combustion), 0°C and 1.013 bar (volume). (Hautaluoma, 2014)
** LNG density at atmospheric equilibrium pressure i.e., 1013.25 mbar absolute
MN calculated by *GasCalc*

3.2.3 Residential & Commercial Applications

The current Finnish national gas grid or the pipeline-specs gas has the following limits. The same gas is utilized in residential and commercial sectors. It is tabulated hereunder in Table 11.

Table 11 (Gasum Oy., 2012) (Gasum Oy., 2014) (Rintamäki, 2014) (Niskanen, 2013): Current Finnish natural gas grid and its Quality Regulations of natural gas as injected to Gasum transmission system

Property/ Component	Unit	Gasum pipeline[&]						Siberian Gas	Quality specs of NG injected to transmission system[#]
		December 2013			2013				
		Min.	Max.	Avg.	Min.	Max.	Avg.		
Methane number		91.94	91.05	91.56			91.66		101.4
Methane	mol %	97.017	97.447	97.282	96.602	97.878	97.356	98.4	≥ 95
Ethane	mol %	1.518	1.977	1.679	0.906	2.448	1.464	0.6	
Propane	mol %	0.145	0.195	0.171	0.143	0.446	0.268	0.2	
i-Butane	mol %	0.039	0.045	0.042	0.039	0.076	0.051		
n-Butane	mol %	0.021	0.028	0.024	0.020	0.075	0.042	0.05	
i-Pentane	mol %	0.004	0.005	0.004	0.004	0.014	0.008		
n-Pentane	mol %	0.003	0.004	0.003	0.003	0.010	0.005	0.01	
Hexane+ (C6+)	mol %	0.003	0.007	0.005	0.002	0.013	0.005	-	
Nitrogen	mol %	0.511	0.634	0.588	0.407	0.812	0.673	0.8	
Nitrogen + Argon	mol %								≤ 3
CO_2	mol %	0.168	0.270	0.202	0.032	0.293	0.127		≤ 2.5
CO_2+CO	mol %								≤ 2.5
Oxygen	mol %			0			0		traces
Hydrogen sulfide (H_2S)	mg/Nm^3								≤ 15
Sulphur, mercaptan	mg/Nm^3								≤ 25
Total Sulfur (as Sulfur)	mg/Nm^3							< 1	≤ 100
L. Calorific value	MJ/Nm^3	36.195	36.324	36.249	36.083	36.507	36.268	10 kWh/Nm^3 [36 MJ/N m^3]	
H. Calorific value	MJ/Nm^3	40.141	40.280	40.199	40.021	40.477	40.220		38.663 – 41.360
Gross Wobbe Index	MJ/Nm^3								13.76-15.81 kWh/Nm^3 [49.536-56.916 MJ/Nm^3]
Lower Wobbe Index	MJ/Nm^3	47.968	48.028	47.996	47.909	48.167	48.019		
Density	kg/Nm^3	0.736	0.739	0.7375	0.733	0.743	0.737		
Relative Density		0.569	0.572	0.570	0.567	0.574	0.570		0.555-0.700
Particulate matter size	micron								≤ 3
Hydrocarbon dew point at 40 bar	°C								≤ -9
Water dew point at 40 bar • winter • summer	°C	-36.127	-33.275	-34.789	-36.128	-5.531	-26.45		≤ -5 ≤ 0

Heating value calculated as per ISO-6976 at combustion temperature 25°C, and MJ/Nm^3 (volume metering reference conditions) is at 0°C, 1.01325 bara
The values are based on "Common Business Practice, Harmonization of Natural Gas Quality 2005–001/01" published by EASEE-gas. (Gasum Oy., 2012)
[&] Analysis of incoming gas received at Imatra (online record – average values are based on daily averages and rounded-off to third decimal) (Gasum Oy., 2014) (Rintamäki, 2014)
MN is calculated by *GasCalc* AVL-method. MN has not been specified by Gasum for gas injection to Transmission system.

For the above Gasum data, Combustion reference temperature is +25°C and pressure 1.01325 bara; Volume metering reference is 0°C and 1.01325 bara everywhere else except in Imatra border station (the custody transfer point for Russian gas entering Finnish grid) where measurement is done for the gas volumes coming from Russia at volume reference +20 °C and 1.01325 bara. The combustion reference is +25 °C and 1.01325 bara also in Imatra border station. (Rintamäki, 2014)

Furthermore, the calculations for the Heating Value, Wobbe and Compression Factor are on Dry, Real basis. There is no (or negligible) amount of sulphur and oxygen in the current Russian gas supply to Finland (Rintamäki, 2013). Water and sulphur are also neglected in these heating value, Wobbe Index and compression factor calculations. Calculations are made according to ISO 6976:1995 (At custody transfer point Imatra, these values are calculated in both volume metering temperatures: 0 °C and 20 °C). If conversions are needed, ISO 6976:1995 - Annex J is normally used (which has the same basic information as ISO 13443:1996). (Rintamäki, 2014)

In order to have true picture of existing grid customers, the latest Gasum pipeline gas data of December 2013 was incorporated along with that of the whole year 2013 based on average values from daily averages (shown in table 12). In addition, the standard set by Gasum for injection of any gas to their pipeline, was plotted in the diagram, though its MN (calculated by *GasCalc* AVL method) is higher (101.4) which may be due to addition of inerts like nitrogen and CO_2.

3.3 Available Quality of Natural Gas

Finnish natural gas grid is wholly based on imports from Russia. Therefore, the current quality of pipeline-gas in Finland is the same as given in table 12. Similarly, the LNG quality currently available for Finnish market is that of the indigenously produced LNG at Gasum Porvoo plant described in table 11. A search was conducted to trace LNG production sources in the world and LNG re-export terminals (particularly in Europe) with their detailed LNG specifications.

3.3.1 Global LNG Sources and Specifications

On the global level, the LNG is produced and exported by 17 countries (International Gas Union (IGU), 2013) from variety of sources with differing composition and type of natural gas. Table 12 below shows the updated characteristic of LNG sources in detail.

Table 12 (International gruop of liquefied natural gas importers (GIIGNL), 2012): Global LNG Specifications 2012

Origin	Nitrogen N_2 %	Methane C1 %	Ethane C2 %	Propane C3 %	C4+ %	TOTAL	LNG Density[1] kg/m³	Gas Density[2] kg/m³(n)	Expansion ratio m³(n)/ m³ liq	Gas GCV[2] MJ/m³(n)	Wobbe Index[2] MJ/m³(n)
Australia - NWS	0.04	87.33	8.33	3.33	0.97	100	467.35	0.83	562.46	45.32	56.53
Australia - Darwin	0.10	87.64	9.97	1.96	0.33	100	461.05	0.81	567.73	44.39	56.01
Algeria - Skikda	0.63	91.40	7.35	0.57	0.05	100	446.65	0.78	575.95	42.30	54.62
Algeria - Bethioua	0.64	89.55	8.20	1.30	0.31	100	454.50	0.80	571.70	43.22	55.12
Algeria - Arzew	0.71	88.93	8.42	1.59	0.37	100	457.10	0.80	570.37	43.48	55.23
Brunei	0.04	90.12	5.34	3.02	1.48	100	461.63	0.82	564.48	44.68	56.18
Egypt - Idku	0.02	95.31	3.58	0.74	0.34	100	437.38	0.76	578.47	41.76	54.61
Eqypt - Damietta	0.02	97.25	2.49	0.12	0.12	100	429.35	0.74	582.24	40.87	54.12
Equatorial Guinea	0.00	93.41	6.52	0.07	0.00	100	439.64	0.76	578.85	41.95	54.73
Indonesia - Arun	0.08	91.86	5.66	1.60	0.79	100	450.96	0.79	571.49	43.29	55.42
Indonesia - Badak	0.01	90.14	5.46	2.98	1.40	100	461.07	0.82	564.89	44.63	56.17
Indonesia - Tangguh	0.13	96.91	2.37	0.44	0.15	100	431.22	0.74	581.47	41.00	54.14
Libya	0.59	82.57	12.62	3.56	0.65	100	478.72	0.86	558.08	46.24	56.77
Malaysia	0.14	91.69	4.64	2.60	0.93	100	454.19	0.80	569.15	43.67	55.59
Nigeria	0.03	91.70	5.52	2.17	0.58	100	451.66	0.79	571.14	43.41	55.50
Norway	0.46	92.03	5.75	1.31	0.45	100	448.39	0.78	573.75	42.69	54.91
Oman	0.20	90.68	5.75	2.12	1.24	100	457.27	0.81	567.76	43.99	55.73
Peru	0.57	89.07	10.26	0.10	0.01	100	451.80	0.79	574.30	42.90	55.00
Qatar	0.27	90.91	6.43	1.66	0.74	100	453.46	0.79	570.68	43.43	55.40
Russia - Sakhalin	0.07	92.53	4.47	1.97	0.95	100	450.67	0.79	571.05	43.30	55.43
Trinidad	0.01	96.78	2.78	0.37	0.06	100	431.03	0.74	581.77	41.05	54.23
USA - Alaska	0.17	99.71	0.09	0.03	0.01	100	421.39	0.72	585.75	39.91	53.51
Yemen	0.02	93.17	5.93	0.77	0.12	100	442.42	0.77	576.90	42.29	54.91

[1] Calculated according to ISO 6578 [T = -160°C]. [2] Calculated according to ISO 6976 [0°C / 0°C, 1.01325 bar].

However, the data for this work was gathered from Gasum's internal archive and studies, which included 27 LNG sources traced around the world. The composition and properties of these blends were analyzed to acquire the values of MN, LHV and WI interchangeability parameters, and the same have been used for further analysis.

3.3.2 LNG Re-export Terminals

Re-export terminals do not produce LNG, but have the facilities to export the cargoes already imported by them from various origins/ sources. LNG specifications of the following European terminals were found, and compiled in Table 13.

- Zeebrugge Terminal (Belgium)
- GATE Terminal (The Netherlands)
- Klaipeda Terminal (Lithuania)

Table 13 (Fluxys Belgium SA, 2013) (Hammerschmid, 2013) (Mattila, 2014): LNG specifications of LNG re-export terminals

Property/ Component	Unit	Zeebrugge Terminal	GATE Terminal		Klaipeda Terminal
			Gas (GTS Entry)	LNG	
Methane Number		≥ 70.01*	≥ 80#	≥ 80#	≥ 80
Methane	mol%	80-100			≥ 91.5
Ethane	mol%				≤ 7
Propane	mol%				≤ 3
C2 + C3	mol%				≤ 8
C4+ • When C3 ≤ 2 mol% • When C3 > 2 mol%	mol%				≤ 1 ≤ 0.75
Nitrogen	mol%	0-1.2			≤ 5
Gross Calorific Value	kWh/Nm^3	10.83-12.43	39.5-44 MJ/Nm^3	39.5-44 MJ/Nm^3	10.40-12.21
Maximum GCV with QC	MJ/Nm^3		46.7	46.7	
Net Calorific Value	kWh/m^3				9.49-11.00
Wobbe Index (Gross)	kWh/Nm^3	14.17-15.56	49.9-54 MJ/Nm^3	49.9-54 MJ/Nm^3	14.02-15.51
Maximum WI (Gross) with QC	MJ/Nm^3		57.2	57.2	
LNG density at atmospheric equilibrium pressure, i.e., 1013.25 m bara	kg/m^3 LNG	425-480			
Relative density					0.55-0.62
iC4	mol %	≤ 1			
nC4	mol %	≤ 1			
iC5	mol %	≤ 0.20			
nC5	mol %	≤ 0.20			
C6+	mol %	≤ 0.10			
H_2S + COS (as Sulfur)	mg/Nm^3	≤ 5	≤ 5	≤ 5	≤ 0.007
Mercaptans (as Sulfur)	mg/Nm^3	≤ 6	≤ 5	≤ 5	≤ 0.016

Total Sulfur (as Sulfur)	mg/Nm^3	≤ 22.4	≤ 30	≤ 30	< 0.03
Oxygen	vol%	≤ 10 ppmv	≤ 0.0005	≤ 0.0005	≤ 0.02
CO_2	vol%	≤ 100 ppmv	≤ 2	≤ 2	≤ 2.5
CO	ppmv	≤ 1			
Hydrogen	ppmv	≤ 1			
H_2O	ppmv	≤ 0.1			
Mercury	nano g/Nm^3	≤ 50			
Water dew point at delivery pressure	°C		≤ -8 (at 72 barg)	≤ -8 (at 72 barg)	< -10 (at 4 MPa)
Hydrocarbon condensate content (at -3°C & delivery pressure)	mg/Nm^3		≤ 5	≤ 5	
Solids (on 32 mesh strainers)		0			
Hydrocarbon dew point (cricondentherm)	°C	≤ -20 (1-70 bara)			< -2 (2.5-7.5 MPa)
Water & hydrocarbon content in liquid phase					0
Mechanical impurities	g/m^3				≤ 0.001
Temperature trunk–line entry point	°C		0-40		
Maximum trunk-line pressure	barg		≤ 79.9		

* MN calculated by GRI Linear Correlation Method

[#] recommended by Gasunie Transport Services (GTS) (Gasunie Transport Services, 2014)

The bulk of this data has been utilized to build a database to serve the purpose of analytical comparison.

4. Comparison of Specifications

After a thorough analysis of the whole data of natural gas specifications for Finnish market, the available and required properties were compared and contrasted. A variety of units and reference conditions were quoted by the manufacturers for the collected data, which were converted to combustion and volume-metering reference conditions of 25°C, 101.325 kPa and 0°C, 101.325 kPa respectively. The whole process resulted in defining the confines or windows of concerned sectors considered by this study. Three most relevant quality parameters, lower heating value (LHV), lower Wobbe Index (shortly called as Wobbe Index here, WI) and methane number (MN) were selected for comparison of the characteristic data of all the designated sectors in Finland by creating three plots LHV-MN, LHV-WI and MN-WI; these constructed maps are elaborated in this chapter.

The harvested data from the selected segments of LNG or natural gas applications was interpreted in the form of "quality windows".

4.1 Quality Windows for Different Sectors

The data provided by several manufacturers/ users consisted of mainly the single values of a particular parameter (i.e. minimum requirement) necessary for the optimum performance of the concerned application. Generally, they did not quote the range or operating brackets of the properties in which the application, for example an engine, performs at best efficiency. Another trend was to specify only the upper or lower limit of the parameter which again did not serve the purpose of determining the working confines of the specie. Since, almost all the values collected from market were meant for optimal operation, the data has been compiled by taking into account these minimal figures for MN, LHV and WI only.

In order to evaluate this type of data-sets comprising the minima and maxima for boundary conditions, usually 4 possibilities exist:

a) By considering the lowest of the minima and the largest of the maxima; this commonly determines the whole value range of data on a number line
b) By taking largest of the minima and lowest of the maxima; this typically outlines the common set of values for all the data-sets.

c) By accounting for both the lowest and the largest of only maxima; this defines the comparison of the merely upper most or ending values

d) By examining both the lowest and the largest of only minima; this compares only the starting values

In the present case, tool ‘a’ and mostly ‘b’ has been utilized for data analysis for two reasons, firstly this study is aimed at assessing the common requirement of all the uses and secondly these represent the whole data range rather than focusing on the lower and upper portions of data samples. In the case under consideration, method ‘c’ would pose the most stringent requirement for all the sectors, which is an expensive option. Even though it is uneconomical, yet it has been worked out and displayed on the maps for the sake of a pragmatic idea of meeting the toughest market demand, as it guarantees the 100% fulfillment of every requisition.

A total of 15 graphs are plotted (3 for each of 5 denominations) using tool ‘a’ and ‘b’. One such plot for the marine sector is shown here in Figure 4.1-1; further graphs for the marine, land traffic, gen-sets, burners, and grid are attached in Appendices 1-5 in that order. Rectangular areas are constructed showing the limit of all the applications.

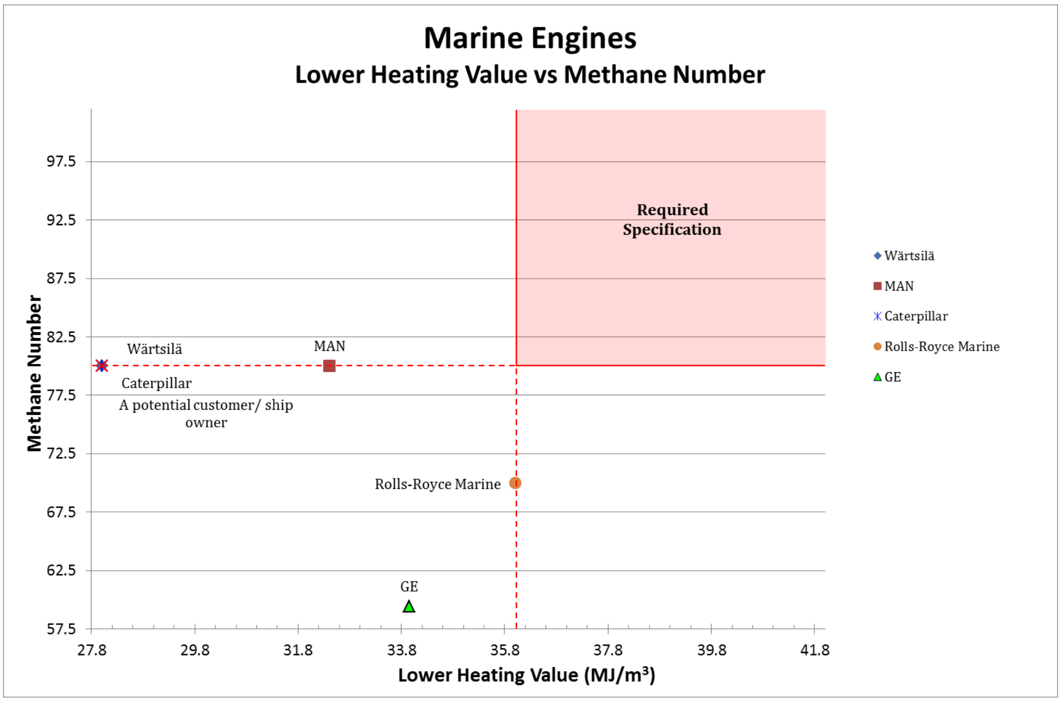

Figure 4.1-1: LHV-MN plot for Marine Sector

The demand of a potential ship-fuel customer is also incorporated to know the tendency of future market. Upper boundary limits were not mentioned by any market source in this sector.

For the land traffic sector, data mostly belongs to the heavy-duty vehicles (trucks); only Volvo supplied the boundary limits of lower Wobbe Index for their LNG truck, while Scania quoted the limits for HHV and gross Wobbe Index. Several values were calculated based on the received information, and the current UNECE regulation for vehicle homologation is also depicted in the graph using the CEN-defined G20, GR, G23 and G25 reference gas fuel specifications as referred by Table 7. It is noted that although UNECE fuels cover most vehicle brands, yet few, such as Cummins and Scania, lie outside this boundary. Figure 4.1-2 shows this phenomenon with overlapping areas formed by various vehicle engine-makes, for which the upper bounds were supplied. Other maps are available in Appnendix-2.

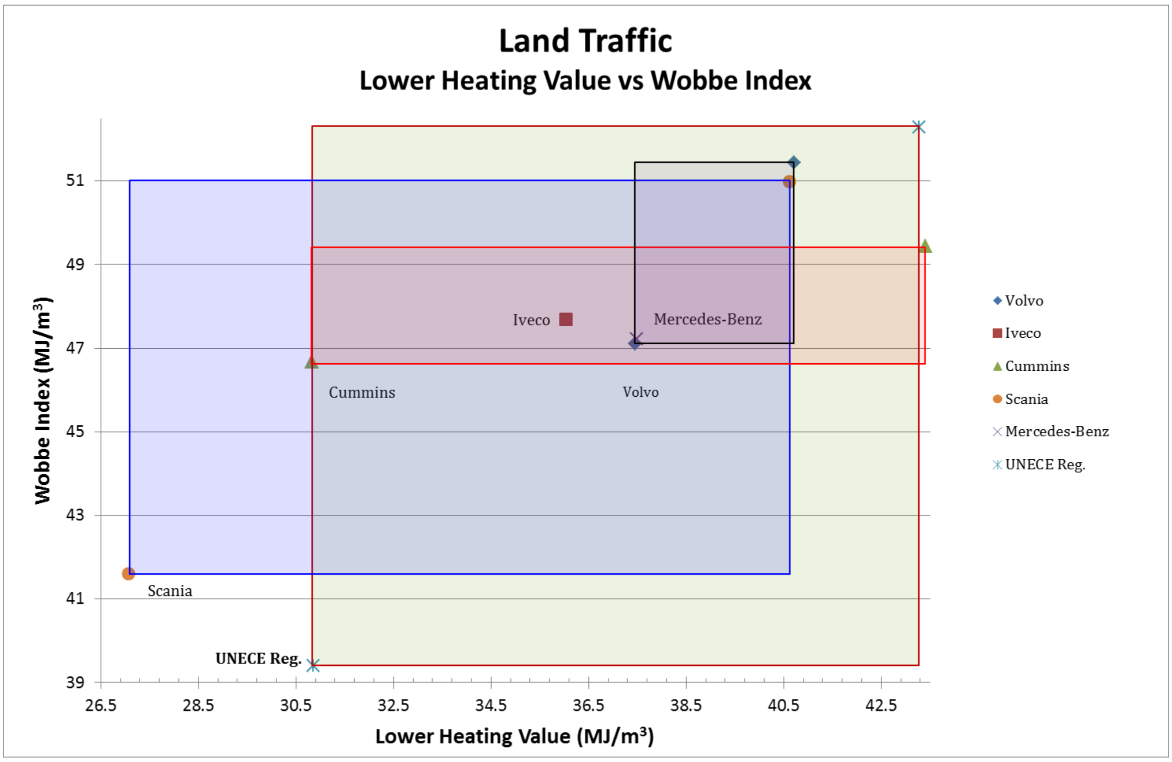

Figure 4.1-2: LHV-WI diagram for Land Traffic Sector

Same process was carried out with the Gen-sets and Burners categories and their area of operation was determined and displayed in the shape of rectangles or windows.

In Burners & Boilers sector, specifications for L-, H-, E-, and LL-gas were forwarded by different burner makers; however, the H- and E-gas types were selected by matching them with the prevailing practice in Finland. Following Figures 4.1-3 and 4.1-4 explain the windows representing these sectors. Other plots are given in attached Appendix-3 and 4.

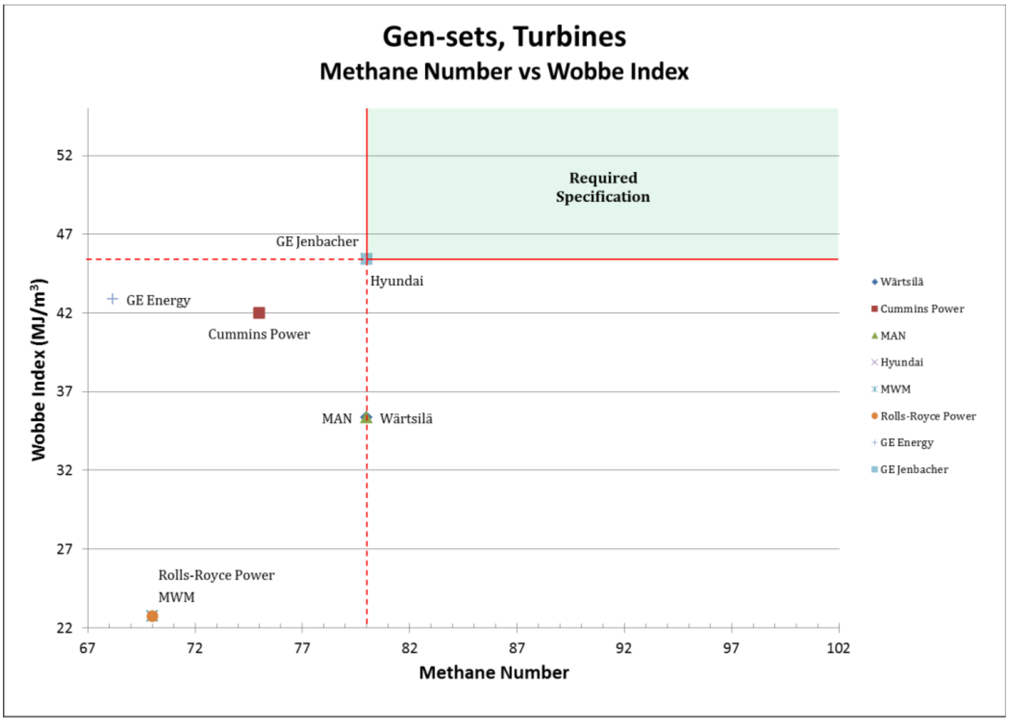

Figure 4.1-3: MN-WI window of Gen-sets, Turbines sector

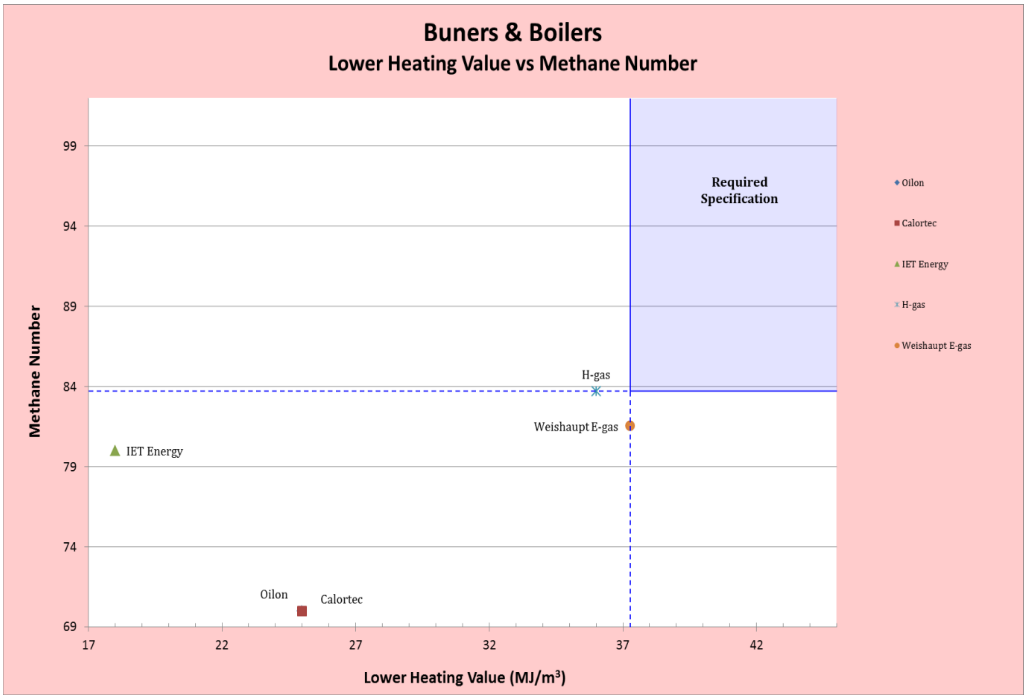

Figure 4.1-4: LHV-MN chart of Burner & Boilers sector

The natural gas grid of Finland, operated by Gasum, bears consistent composition and characteristics, as shown in Table 11, due to absence of any comingle gas. Therefore, the grid diagrams almost coincide for the grid properties, however the boundary values for Gasum transmission pipeline are shown in the form of a window, surrounded by H-group fuel gas specifications to which the Finnish natural gas belongs, as illustrated in Figure 4.1-5. Other plots are attached in Appendix-5.

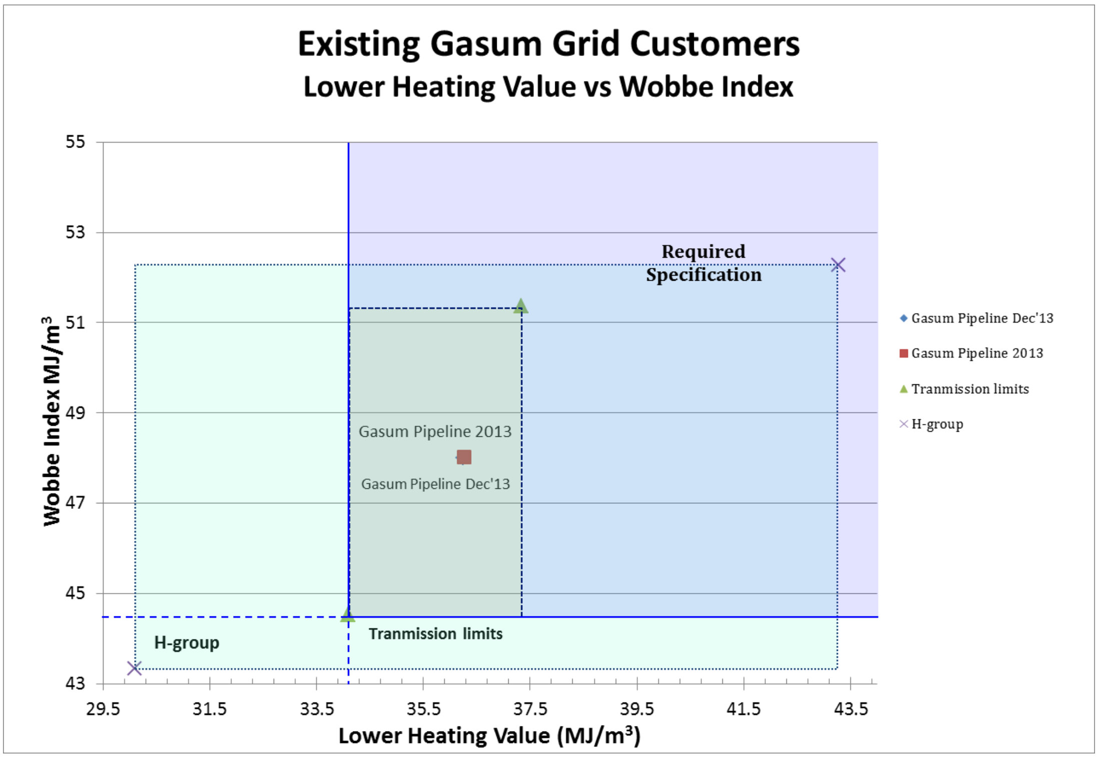

Figure 4.1-5: LHV-WI graph of Gasum grid

Current pipeline natural gas in Finland belongs to the H-group of 2nd family gases according to nomenclature by European standard EN 437, and as per the same standard, test gases for this group are G20, G21, G222 and G23 with the following composition as per Table 14. (CEN, 2003)

Table 14 (CEN, 2003): Reference and Test gases for 2nd family H-group

Component	Unit	G222	G23	G21	G20
Methane	mol %	77	92.5	87	100
Ethane	mol %	23	-	13	-
N_2	mol %	-	7.5	-	-

These blends cover the whole gas appliances using the Finnish H-group gas. Their methane number, and lower heating value and lower Wobbe Index were calculated by ISO 6976:1995 at the required reference conditions (25°C, 0°C, 1.01325 bar). Subsequently, graphical windows were plotted by taking the limit values of these parameters. This window actually defines the working area of all residential, commercial gas appliances in Finland. Secondly, three types of burners (two single-category and one double-category) are used in the country, namely I_{2H}, $I_{3B/P}$, $II_{2H3B/P}$ (CEN, 2003). Single-category burners are able to work with just one family of fuel gases, whereas double-category ones can work by using fuel gases from two families. The subscript in the burner name depicts type of group which can be used in that particular burner type. Thus, burners in Finland utilize either 2nd family H-group or 3rd family B/P-group or both; this 3rd family basically specifies liquefied petroleum gas (LPG) comprising higher hydrocarbons and therefore higher heating values, densities and Wobbe Indices. These 3rd family fuels are out of scope for this study, yet if it is also taken into consideration, the working window for appliances would be more widened.

4.2 Common Demand of All Sectors Combined

The requirement of the individual sector is drawn for these maps which defines demand windows of each sector in all the three categories of graphs. This discrete window of each sector is further put on a single map for each of three plot-categories by superimposing, thereby creating a rectangular area, common to all sectors. The individual sector-wise common values with 5% tolerance for the investigated parameters are shown below in Table 15.

Table 15: Initial operating band (the minimum requirement) of various sectors individually against investigated parameters

Sector	Methane Number	LHV	Wobbe Index
		MJ/Nm^3	MJ/Nm^3
Marine Traffic	80	34.2	45.42
Land Traffic	83	35.6	45.31
Gen-sets, turbines	80	34.2	43.17
Burners & boilers	80	35.4	45.46
Existing Gasum grid	87.08	34.1	44.52

The calculation is based on the minimum values for optimum performance. The windows could be well constructed if the minimum and maximum values would be available, but all the representative data only contained the lower boundary limit, except a couple of manufacturers who furnished the upper limit values, which is such small data sample that no authentic opinion can be based on it. Statistically, existence of a final bound or limit is essential to establish a closed shape to base a finding.

In order to address the issue, the only authentic available conditions, the Gasum standard boundary conditions for Transmission pipeline were assumed to be the final values for this data given in Table 15, to frame conclusions from it. This choice makes logic since Gasum border values encompass more than 97% data gathered from the market, and more importantly the imported LNG would mainly be transported by injection to existing pipeline from the Finnish import terminal. These boundary conditions for Gasum grid are only specified for Higher Heating Value (38.663 – 41.360 MJ/Nm^3) and Higher Wobbe Index (13.76 kWh/Nm^3 – 15.81 kWh/Nm^3 i.e. 49.536 – 56.916 MJ/Nm^3) from TSO rules (Rintamäki, 2014). Sine methane number is not specified by Gasum, the calculated values of MN for Gasum pipeline gas average composition of 2013 have been used with applicable tolerance. The upper value of MN is taken as 101.4, as per calculation by GasCalc software with composition of Gasum Transmission limits.

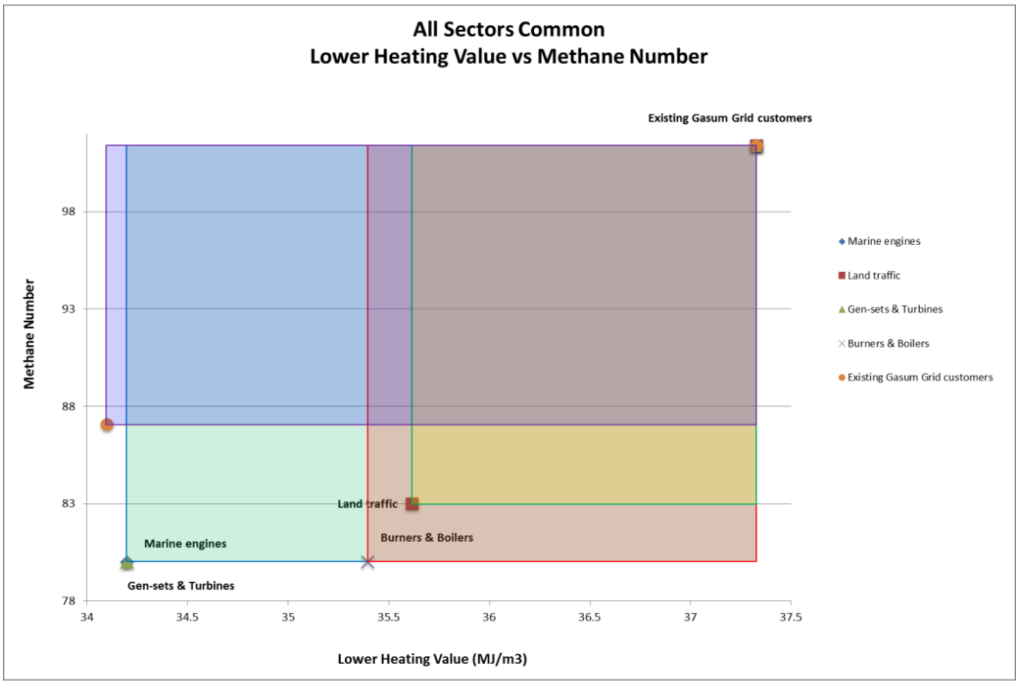

Figure 4.2-1: Construction of windows for all sectors on LHV-MN plot

With the end limits set, the data was portrayed in the form of proper windows on the same parametric graph pattern, and was further analyzed to define the range (Finnish Demand Range) and common band (Finnish Common Demand). Figure 4.2-1 shows an LHV-MN graph with the actual situation of various sectors. The limit values are constructed into windows for every sector on the same scale while they overlap to outline an area shared by all. This area (the gray-coloured square) is the common window which defines the requirement position (the Finnish common demand band) of all sectors with respect to two interchangeability parameters drawn along the axes of the chart.

Similarly, mutual windows are constructed for all sectors on LHV-WI and MN-WI charts (given in Appendix-6), which are in fact visual representation of one combined demand of LNG/ natural gas for Finnish market.

4.3 LNG Variety Available Worldwide

Subsequent to collection of 27 global LNG sources and 3 LNG re-export terminal data with their calculation of their properties, the same are plotted on a scatter graph against the parameters under consideration, thus creating 3 separate graphs showing position of each source in line with its characteristics. An LHV-MN picture is shown here in Figure 4.3-1, rest of the pictures are enclosed in Appendix-7.

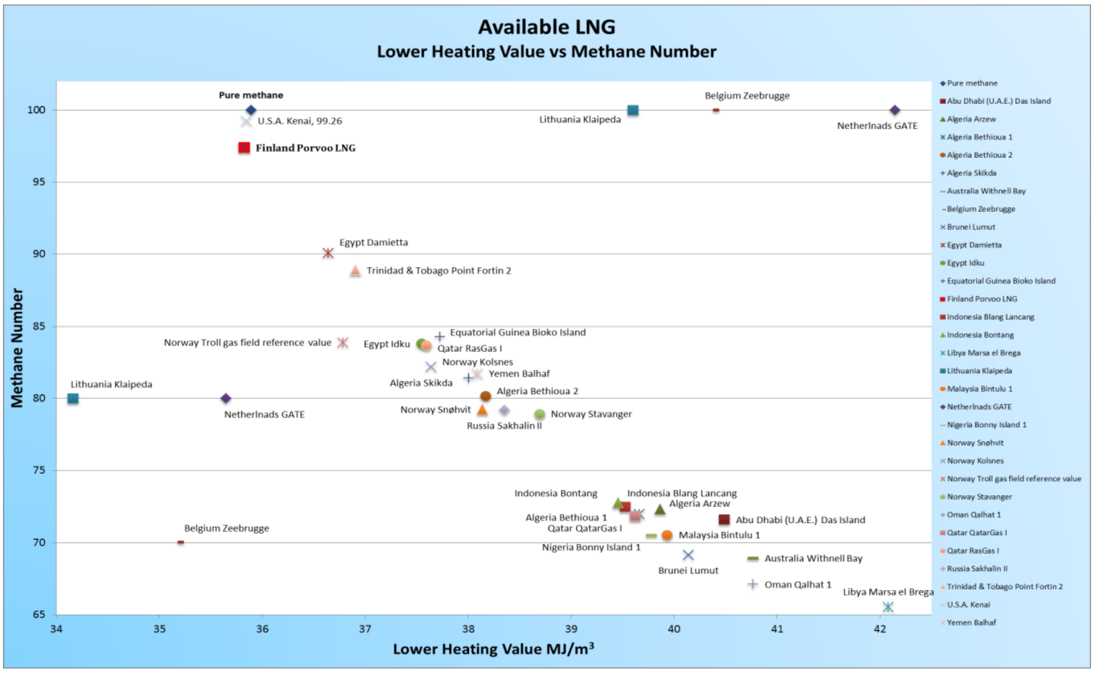

Figure 4.3-1: Global availability of LNG sources shown on MN vs LHV plot

The maximum allowable values of only HHV and WI for the Gasum transmission system were accessible, which have been used to specify the end bounds of the parameters.

4.4 Demand-Supply Assessment

After the evaluation of the requirement and the availability, the data was subjected to find out viable LNG supply sources satisfying Finnish natural gas applications. The common windows built for all sectors were overlaid on the available LNG plot, which in turn framed out the LNG sources acceptable for the Finnish market (as shown in Figure 4.4-1); LNG from these sources would not necessitate any additional treatment for utilization in Finnish market.

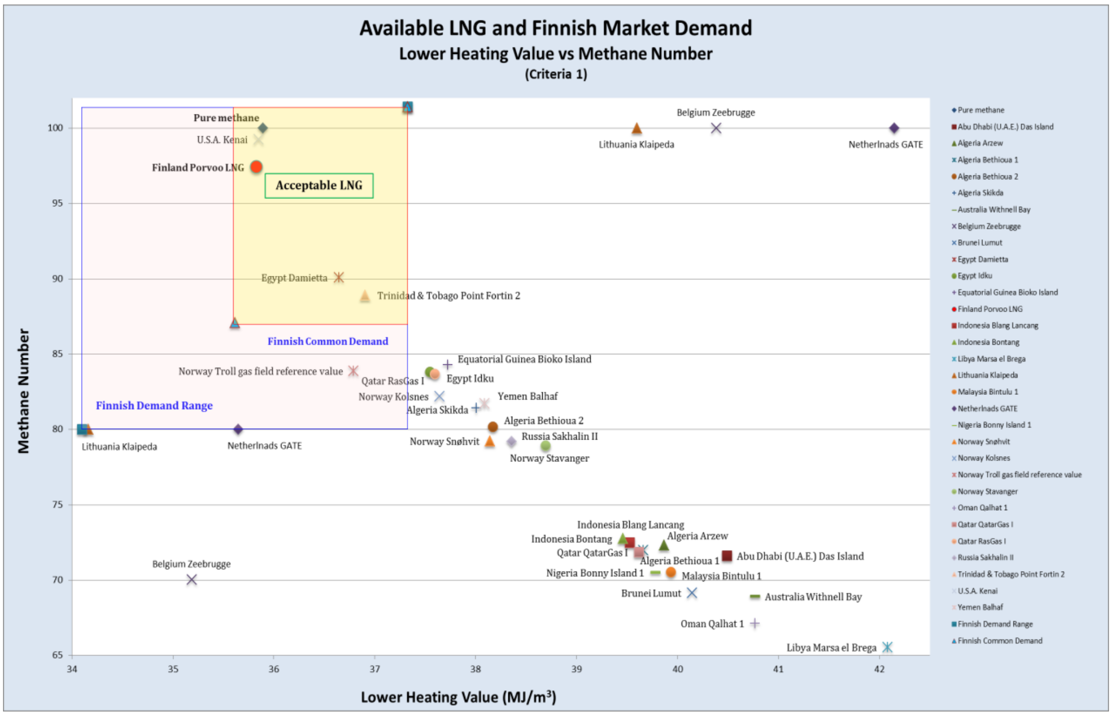

Figure 4.4-1: LHV-MN map for Criteria-1

In context of the re-export terminals, 3 such terminals have been included in the LNG sources in this study, however, they are different in nature from the actual sources. The source produces a gas of specific properties (single quality) and there is normally no sizeable change in it whereas the re-export terminals have options to receive, store and transfer variety of LNG qualities. Thus, quality specifications of such terminals are largely broader and usually span most of the requirements of international market. Same is the case in this work; it is observed that while the acceptable LNG sources are scarce, these 3 re-export terminals are permanently present with their availably area (the specs bracket) covering some, if not all, the demand window of Finnish market. Therefore, this analysis has been carried out mainly considering sources while it is understood that these terminals can supply LNG to suit Finnish natural gas market in any case.

Major concern arisen during the analytical process, was a high methane number demand by Finnish grid, since Gasum grid has high value of methane number, statistically it maintained an MN of 91.66 for year 2013 (91.56 is average of December 2013) Gasum pipeline gas has almost negligible variance in its MN while rest of the sectors already end their common point at 83. The minimum MN (87.08)for Gasum grid was achieved by introducing a tolerance level of +/- 5%. Since this variance limit is already in practice in gas industry (Riikonen & Pihalainen, 2011), it can be exploited here to assess the supply-demand situation.

This is to be noted that around 43% of natural gas applications entailed an MN of 80 whereas about 36% demanded 70 MN as per the data collected for this study.

As depicted in Table 16, the MN-demand is the most critical and has proved to be the deciding factor for the LNG quality. Moreover, by thorough analysis of the data and subsequent graphical representation (Figure 4.4-1), it was inferred that the maximum allowable limits of other parameters (LHV and WI) also played key role in defining the acceptability of incoming LNG quality. As illustrated in table below, upper limit for Wobbe index (adopted from Gasum) is already high to almost contain that of all available LNG sources, however, the LHV limit fails to cover them.

Table 16: Maximum permissible limits for LHV and WI

Sources	**LHV** (MJ/m^3)		**Wobbe Index (lower)** (MJ/m^3)	
	Min.	Max.	Min.	Max.
Required values (Gasum)	35.6155	37.3285	45.4575	51.3682
World LNG sources	35.8288	42.0802	47.6262	51.4182

Therefore, if this upper bound on LHV is increased, more LNG sources can be accessed, keeping in view the fact that +/- 5% tolerance limit is exercised in the industry.

Because of stringent demand of MN, different criteria were built to extend the range of available options. Existing grid has the largest MN requirement with land traffic sector at the second highest. Under this MN scenario, 4 criteria are developed to set up final demand windows in order to achieve a practical solution.

Criteria 1

This considers the normal range of all sectors as per the collected data.

Criteria 2

This considers the range of all sectors excluding grid MN, but including LHV and WI of grid,

Criteria 3

This considers the range of all sectors excluding Grid MN and Land Traffic MN but including their LHV and WI.

Criteria 4

This criterion is similar to the conditions in Criteria 3 without consideration of the upper boundary limits (i.e., unconstrained).

Criteria 1 is the most stringent as it only allows a natural gas with minimum of 87.08 methane number, as shown in Figure 4.4-1, permitting only 3 sources for Finland, namely

- USA Kenai,
- Egypt Damietta
- Trinidad & Tobago Point Fortin 2

which are only 11% of the available sources. All the other LNGs would have to be processed before distribution in Finnish market. Figure 4.4-1 illustrates criteria 1 on an LHV-MN plot, other 2 plots LHV-WI and MN-WI are attached in Appedix-8.

Criteria 2 relax the MN constraint down to 83 but the valid sources remain the same. It is noteworthy here that 83 MN is required by land traffic which uses only 0.2% share of total natural gas in Finland (Finnish Gas Association, 2013), therefore criteria 3 has been created without accounting for the traffic sector MN.

Although the number of acceptable sources remains unchanged yet it is noticeable that if the upper bound of, for example, LHV is increased, a number of additional sources can be made available for LNG import even in both Criteria 2 and Criteria 3.

Figure 4.4-2, Figure 4.4-3 and Figure 4.4-4 show one LHV-MN map each of the Criteria 2, 3 and 4 respectively, other maps are located in Appendix 9, 10 and 11.

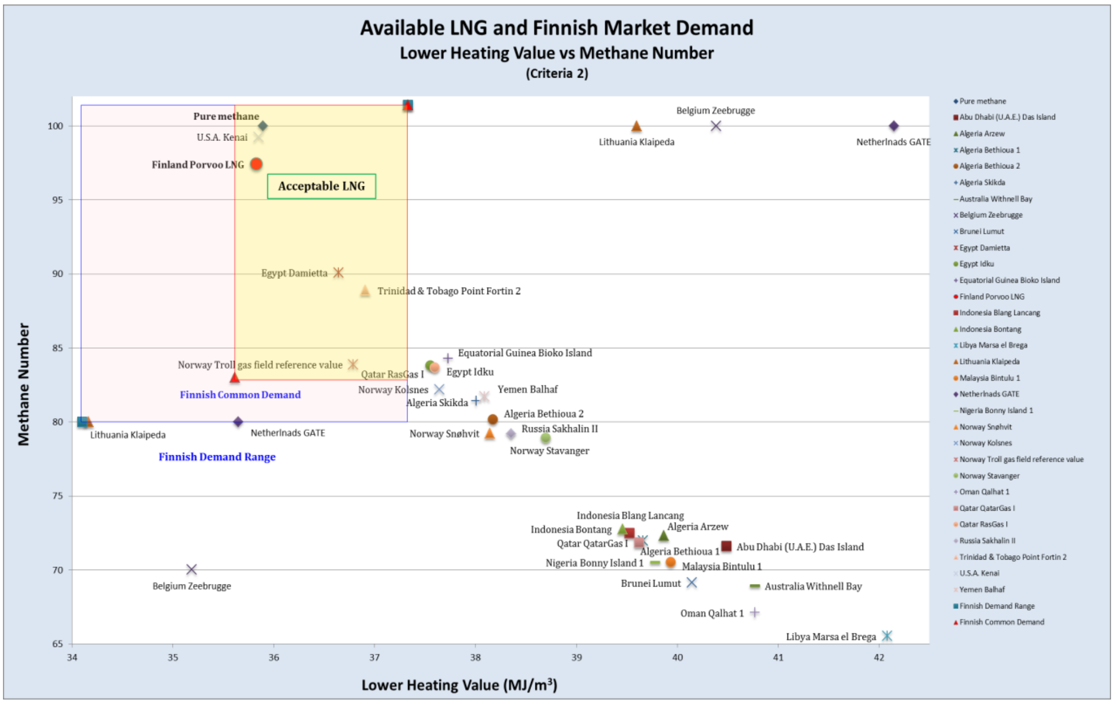

Figure 4.4-2: LHV-MN map for Criteria-2

Criteria 2 and 3 are founded on the fact that if the methane number demand is curtailed from 87.08 to 83 and 80 i.e., by 5% and 8%, more sources can be availed. It is clear that the acceptable LNG remains same in Criteria-2 and 3, in spite of relaxing the MN requirement, which indicates that major issue in this case again remains the tighter maximum allowable limits for LHV. Criteria 4 addresses the problem by only raising (and not completely omitting, although Criteria 4 states this) LHV limit to just 38.17 MJ/m^3 from 37.3285 MJ/m^3 (a 2.25 % rise), thereby increasing the number of LNGs to 11.

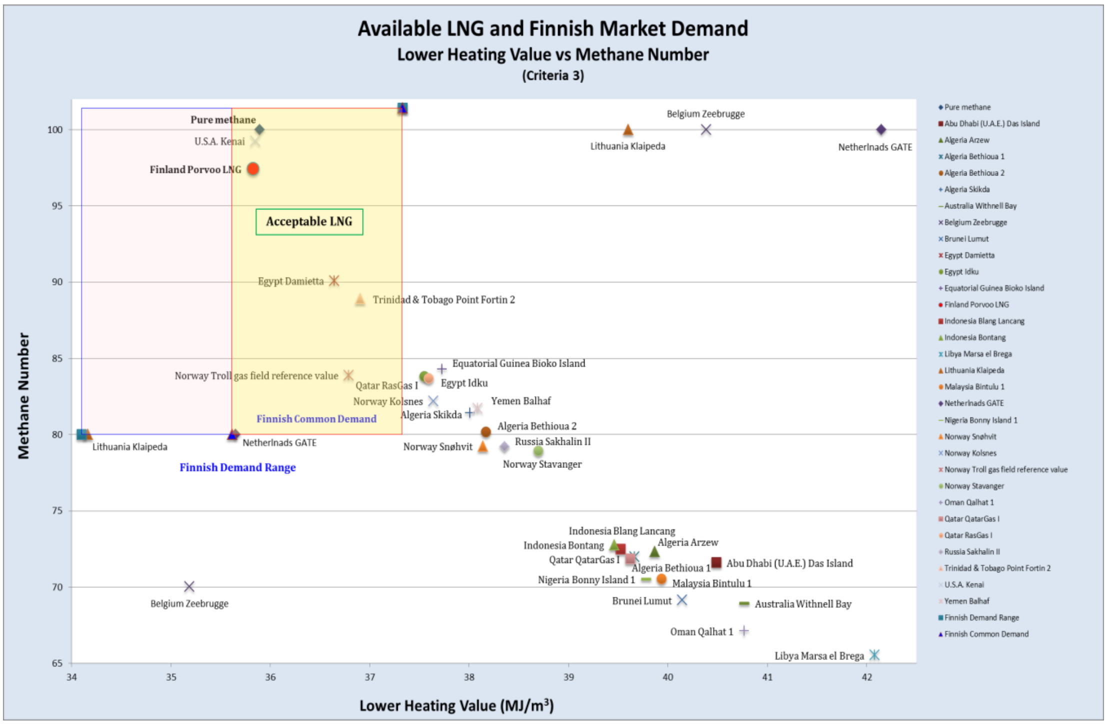

Figure 4.4-3: LHV-MN map for Criteria-3

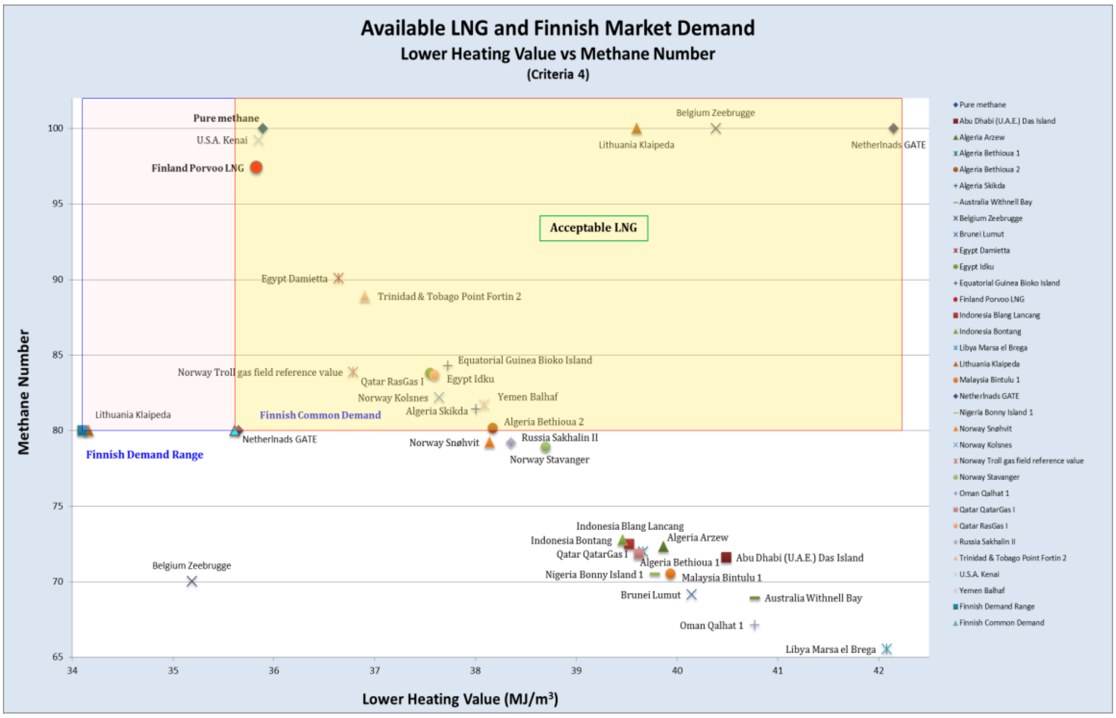

Figure 4.4-4: LHV-MN map for Criteria-4

Modified Criteria

Keeping the LHV upper bound constraint in perspective, a new condition was set up stating a +3% variation (or increment) in the maximum allowable upper limit of lower heating value. With this increase, the LHV value changes from 37.3285 MJ/m^3 to 38.4483 MJ/m^3. On the basis of this condition, Criteria 1-3 were revised (to be called as Modified Criteria) to obtain new results.

The situation remains unchanged in modified Criteria 1with the acceptable sources standing the same 3 (the relevant graphs are attached in Appendix-12), principally due to the higher methane number (87.08) demand by Finnish grid. Nevertheless, modified Criteria 2 enhances the LNG import scope by adding 3 more sources of permissible world LNG, as shown in Figure 4.4-5.

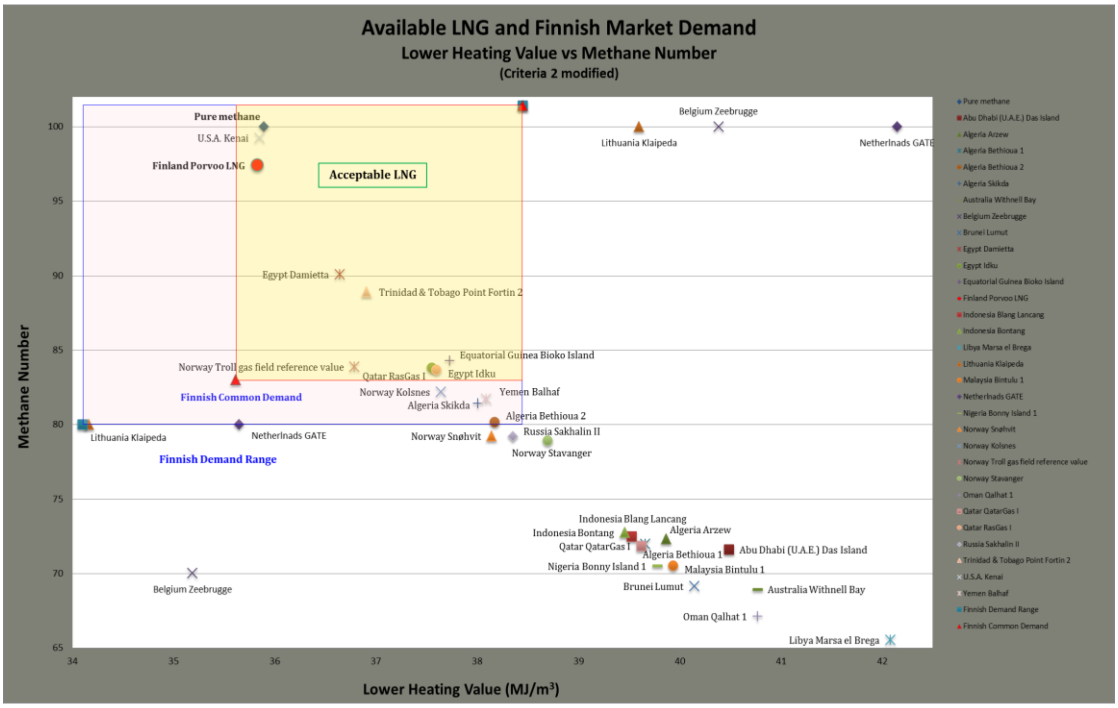

Figure 4.4-5: LHV-MN plot for modified Criteria-2, showing increased range of available sources

Similarly, for modified Criteria 3, the availability of valid LNG resources rises to 11, that is, with MN requirement of 80 and 3% increase of LHV, 11 international LNG producers would be accessible to Finnish natural gas market. Thus, around 41% of world LNG can be tapped with the afore-mentioned conditions, which is practical in the sense that MN 80 commonly fulfils the application demand. Modified Criteria 3 is displayed in Figure 4.4-6 and another LHV-WI plot is enclosed in Appendix-13. The MN-WI plots are not relevant for modified Criteria, since no change has been made in MN and WI, the graphs of these parameters for modified Criteria would remain similar to those in normal Criteria.

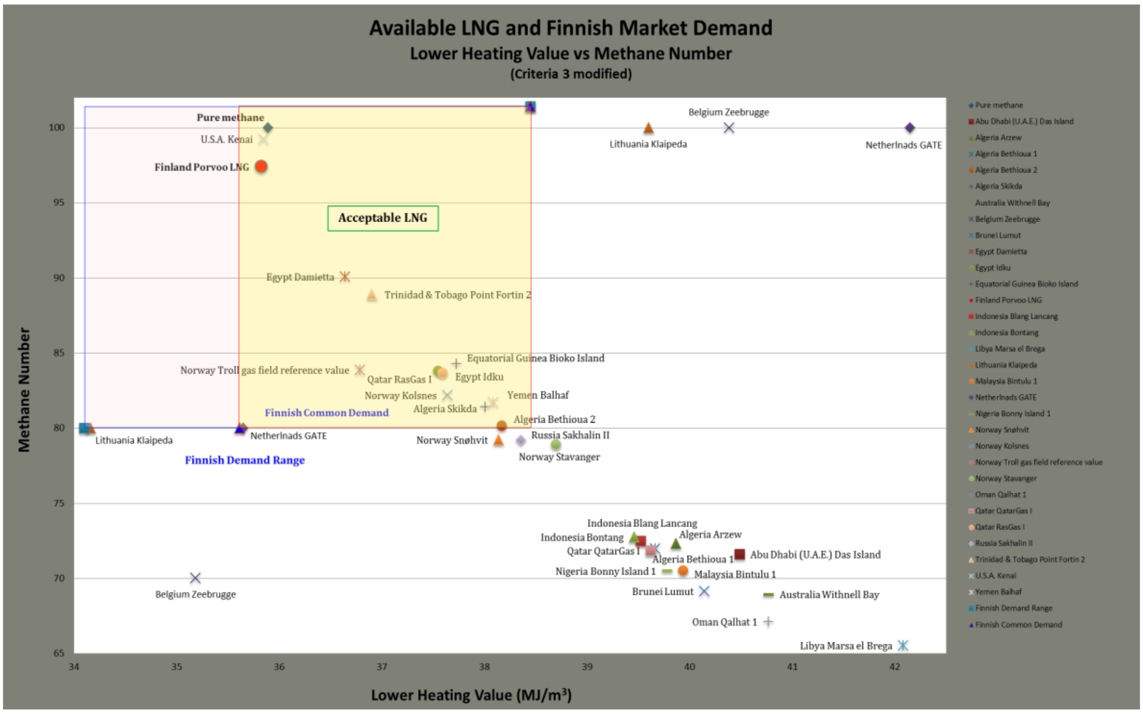

Figure 4.4-6: LHV-MN chart for modified Criteria-3, showing 11 LNG sources available, besides re-export terminals

Established by the above Criteria, the viable sources which do not need additional treatment or conditioning after import are listed here in Table 17.

Table 17: Criteria-wise LNG sources available for import to Finnish market

Sr. No.	Criteria 1		Criteria 2		Criteria 3		Criteria 4
	Normal	Modified	Normal	Modified	Normal	Modified	
1	USA Kenai	USA Kenai	USA Kenai	USA Kenai	USA Kenai	USA Kenai	USA Kenai
2	Egypt Damietta	Egypt Damietta	Egypt Damietta	Egypt Damietta	Egypt Damietta	Egypt Damietta	Egypt Damietta
3	Trinidad & Tobago Point Fortin 2	Trinidad & Tobago Point Fortin 2	Trinidad & Tobago Point Fortin 2	Trinidad & Tobago Point Fortin 2	Trinidad & Tobago Point Fortin 2	Trinidad & Tobago Point Fortin 2	Trinidad & Tobago Point Fortin 2
4			Norway Troll gas	Norway Troll gas	Norway Troll gas	Norway Troll gas	Norway Troll gas
5				Qatar RasGas I		Qatar RasGas I	Qatar RasGas I
6				Egypt Idku		Egypt Idku	Egypt Idku
7				Equatorial Guinea Bioko Island		Equatorial Guinea Bioko Island	Equatorial Guinea Bioko Island
8						Norway Kolsnes	Norway Kolsnes
9						Algeria Skikda	Algeria Skikda
10						Algeria Bethioua 2	Algeria Bethioua 2
11						Yemen Balhaf	Yemen Balhaf

4.5 Sensitivity Analysis of Quality Parameters

As stated in last section, the number of LNG sources can be selected if methane number is decreased. This purpose can similarly be achieved by varying other parameters LHV and WI also, on "what if" principle. The analysis is based on the axioms that

- no upper bounds for parameters are considered
- the source having a value more than or equal to the required value of a parameter would be considered as "acceptable" or "available"
- 27LNG produces exist globally (excluding the re-export terminals)

This builds a basis for the analysis regarding trend and effect of variance in gas quality parameters on the number of permitted LNG sources. MN, LHV and WI were changed in percentages and their resultant influence was observed on the objective function (i.e., number of sources) when plotted on graphical pattern.

The said quality variables were changed from -30% to +30% individually and its effect was observed on the actual number of LNG sources. One parameter was changed at a time while keeping the others constant. The way sources change, shows that they are more sensitive for methane number than LHV and WI; therefore, with 5, 10 and 15% increase in MN 87.08, sources figure decreases from 4 to 2 and 0 respectively; whereas 5 and 10%decrease raises their number from 4 to8, and to 15 which remains unchanged for 15% decrease, as shown in Figure 4.5-1.

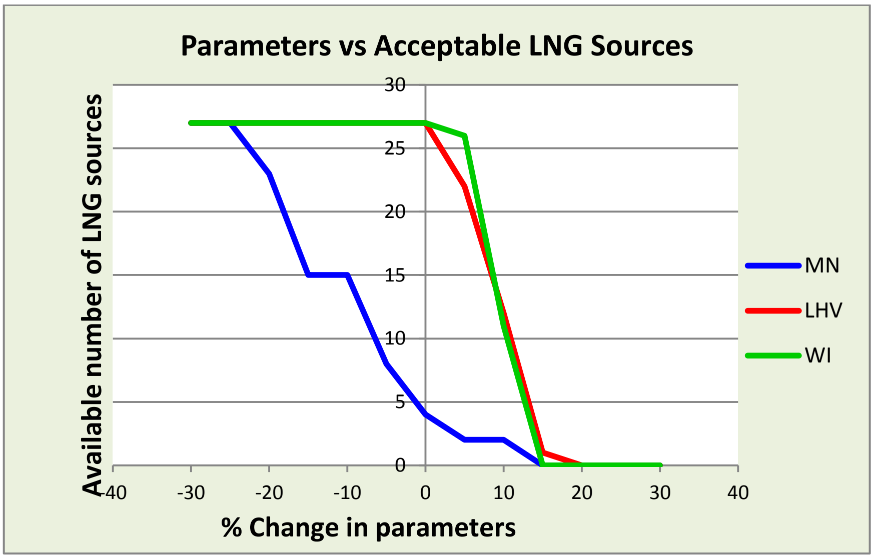

Figure 4.5-1: Impact of change in quality parameter on trend of acceptable LNG sources

All 27 sources remain acceptable for the negative change in LHV and WI, however, for positive variance of +5, +10 and +15% in LHV, the number decreases to 22, 12 and 1 in that order.

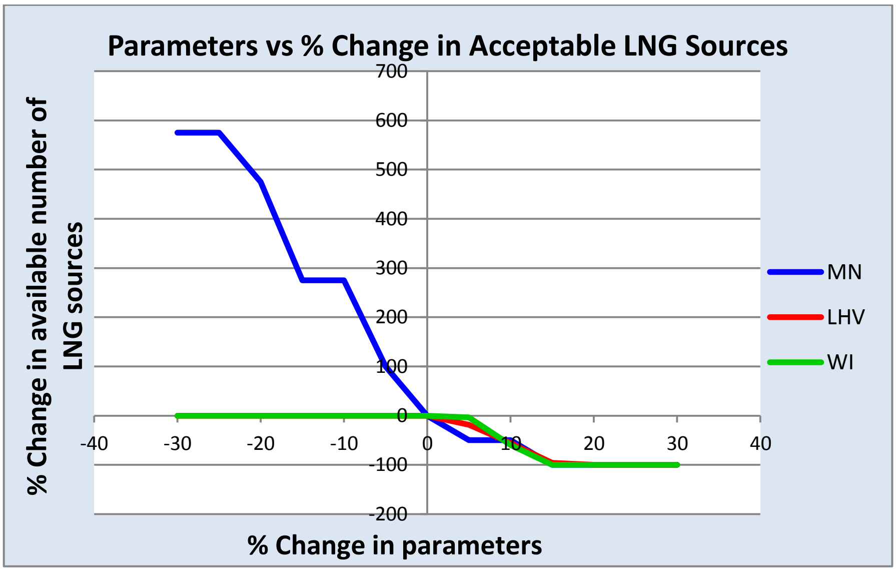

Figure 4.5-2: % change in valid LNG sources with change in gas quality parameters

Similarly, the number of sources is reduced to 26, 11 and 0 for the increase in WI in same change steps. Clearly, no LNG remains available if the parameters are increased beyond 15% (for LHV only, 1 source stays for +15% change).
Same tendency can be monitored in second graph (Figure 4.5-2) more visibly, where the percentage variance in parameters is plotted against percentage change of the number of sources. There is no change in this figure for negative variation (or decrease) of LHV and WI, and after +15% i.e. they remain constant after increase of 15%. This means variation region for the LNG sources only lies between 0-15% of parameter change i.e., all the sources are available for reduced LHV, WI, and none is there for 15% higher LHV and WI. The exponential trend of methane number depicts its highest sensitivity against the accessible LNG.

These plots demonstrate that the relation between gas quality parameters (MN, LHV and WI) and number of LNG sources is non-linear. Although the sources are numerically inversely proportional to the quality variables, yet they are not linearly dependent on the said parameters; the fact explains their uncommon variation pattern.

With the exception of LNG re-export terminals (all of which are capable to meet Finnish market requirement though), availability of LNG is greatly reduced with % increase in the natural gas quality specifications, especially the methane number. Furthermore, the LHV tolerance needs to be increased (in positive direction) in order to avail larger accessibility of world LNG variety.

5. Modeling and Simulation for LNG Quality Management

Numerous environmental friendly regasification solutions signify the growing demand for LNG. As discussed in Chapter 2, though variety of techniques is available to temper with the quality of LNG, this study is focused on the methods applicable at LNG receiving/import terminals mostly because ordering a customized quality to LNG producers is not only cost-intensive but also narrows down the exploitation option of world LNG market.

This chapter presents basic simulation process and compares 3 preliminary models to adjust the quality of imported LNG to reduced heating value. Software tool Aspen HYSYS v8.0 and v8.4 has been used for the process simulations with the SRK Fluid Package.

This is to be noted that the models are elementary and only describe the basic-level viability of LNG quality modification while it is regasified.

5.1 Design Intent

As observed in previous chapters, the Finnish natural gas market has tighter band for heating value, which restricts its choice of using external natural gas. More than 85% of the entire world's LNG sources are inaccessible to Finland because of high heating value than is tolerated here. If the heating value of imported natural gas (LNG) is decreased, it would be acceptable for Finnish consumption. The design intent of this process is to bring the lower heating value (LHV) of the received LNG down to 37.33 MJ/m^3, the upper limit value of Finnish natural gas grid. Thus, LHV is the target parameter/ objective function for the design.

5.2 Basis of Design

In order to decrease the heating value of LNG, design of the process is based on the following grounds.

- Reference feed composition has been taken from QatarGasI (Qatar) LNG, which is given in Table 18.

Table 18: Inlet composition of feed entering the storage tank

Component	Unit	Quantity
Methane	mol%	90.10
Ethane	mol%	6.20
Propane	mol%	2.30
n-Butane	mol%	1.00
Nitrogen	mol%	0.40

- The QatarGas I LNG is presumed to be delivered and stored at a temperature of -161.7 °C and atmospheric pressure (1 bar). The simulation has been performed according to the following process conditions (Table 19).

Table 19 (Gasum Oy., 2014): Process/ Simulation conditions

Parameter	Unit	Provided	Required
Temperature	°C	-161.7	
Pressure	bar	1.01325	45
Lower heating value	MJ/m^3	39.62	≤ 37.33
Lower Wobbe Index	MJ/m^3	50.16	
Relative density		0.624	
Methane number (GRI)		75.8	
Inlet/ Feed flow rate	kgmole/h	100	

- No consideration for commissioning and ATA (annual turn around)/ shutdown conditions have been made.
- Operation is assumed to be on continuous basis.

5.3 Process Alternatives

The key purpose of an LNG receiving terminal is to receive the LNG cargo from ships (LNG carriers), to arrange a proper storage, to re-vapourize it (regasification), and to dispatch it (called sendout) as needed.

The regasification process involves large scale heating of the cryogenic liquid using any type of vapourizer. If the gas is to be injected in high pressure transmission pipeline, the regasified NG would require to be compressed. However, pumps are used generally to pump the NG in its liquid state mainly due to the economical capital and operating cost of pumps compared to the gas compressors. These pumps are capable to increase the LNG pressure normally up to 40 – 240 bars, (Peebles, 1992) such that it passes through the vapourizer and then to the pipeline at required high pressures, thus eliminating the requirement of compressors; this norm is followed by most processors at the LNG receiving terminals.

As described earlier in Section 2.6.1, the reduction of heating value (de-richment) of received LNG can be achieved through various paths. The following 3 methods have been investigated for the study.

1. Extraction of LPG
2. Injection of nitrogen (Nitrogen ballasting)
3. Injection of CO_2 (CO_2 ballasting)

Air ballasting is also popular method but it is not considered here as the oxygen specification is exceeded as per Finnish standards, which do not permit oxygen more than “traces” in natural gas network (Table 11, Section 3.2.3).

The above de-richment methods are briefly illustrated as under.

5.3.1 Case-I (LPG Extraction)

The operating principle of this process is to remove higher hydrocarbons (LPG) or natural gas liquids (NGLs) from the LNG, supplied to import terminals. LPG consists of higher hydrocarbons typically in range of C3-C4 in a natural gas composition; they are the principal reason for larger heating value of a gas blend. LPG extraction directly decreases the heating value by decreasing the concentration of propane and butane in natural gas.

5.3.1.1 Process Description

The process starts with the storage of LNG unloaded from a marine carrier at feed rate of 100 kgmole/h, 101.325 kPa pressure and -161.7°C temperature.

First of all the boil-off gas (BOG), which is taken as 0.08% of the LNG flow rate, is converted to liquid phase (called BOG-handling) by passing it through a re-condenser Rcond at feed temperature and pressure, where it is cooled down before the suction header of the high pressure LNG pump. The Sendout_pump pressurizes the Mixed_LNG stream from 1 bar to 45 bar at -161.7°C temperature, so that LNG is at the threshold injection pressure of the pipeline, after regasification. The pumping operation creates a temperature difference of only 2°C.

This high pressure LNG stream press_LNG is then vaporized by provision of heat as it travels through heat-exchanger Vapourizer. The removal of liquid fraction of the LNG starts from here which continues when it traverses flash operation in three stages with heating arrangement. The Vapourizer increases the temperature of M_lng stream to -71.79°C which enters the 1st separator V-101 at flow rate of 116.9 kgmole/h. About 45% of this stream is sent to final natural gas header from top of the column, and the rest q1_lng is retained at bottom to enter the second separator through heater E-102 at temperature of -67.43°C and feed rate of 64.28 kgmole/h. The 2nd stage V-102 removes 70% of this feed from bottom as liquid, and the 3rd V-103 separates 75% of leftover stream q2_LNG at temperature of -61.88°C. This process actually causes the reduction of LNG heating value. The vapour streams NG, V and V1 are the lean gases sent for pipeline injection. After the vapour-liquid separation, the liquid part (the higher hydrocarbons) L1 at the end of third separator, is the so called, LPG. Around 50% of this LPG is re-circulated through RCY-1 to get better yield of natural gas. Extract_LPG is the LPG sent to storage or dispatch. The recycle stream Recyc is mixed with press_LNG at MIX-102, prior to Vapourizer. The vapour streams from the separators are collected at MIX-101; mix_NG is the required product with minute portion of liquid still present. This liquid is stripped of in the form of condensate in a knock-out vessel. The gas NG_pipeline from top of this vessel is the actual gas of desired heating value and delivery pressure, ready to be injected to the pipeline grid. Figure 5.3-1 elaborates the simulation diagram of the process.

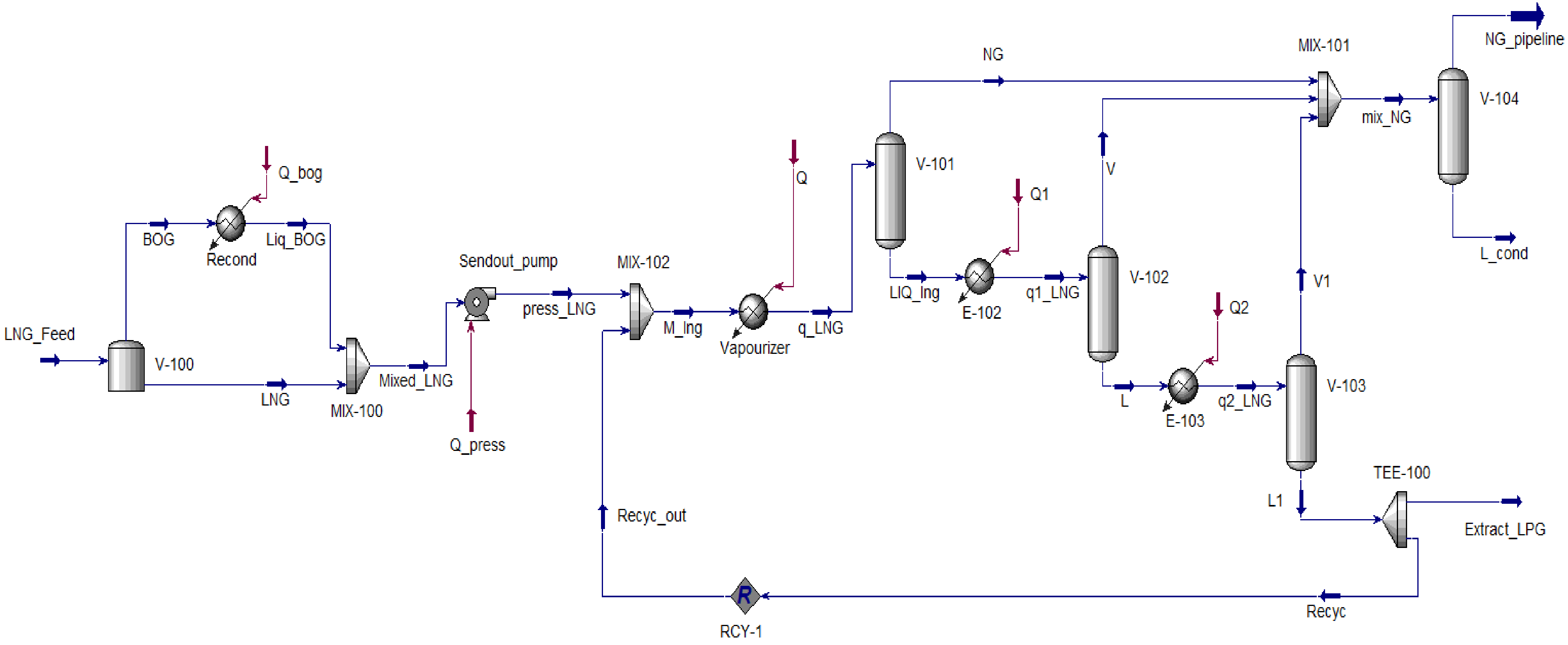

Figure 5.3-1: Simulation layout of LNG quality adjustment process by LPG extraction (Case-I)

5.3.1.2 Separation Efficiency

Vapour-liquid separation is the prime unit operation involved in the process, which has been achieved through 3-staged flash units. Since this VL-separation is the key step to attain required product quality (i.e., high methane concentration), a high separation efficiency is essential for economy of the process. Figure 5.3-2 shows the total separation efficiency as it changes after each flash stage.

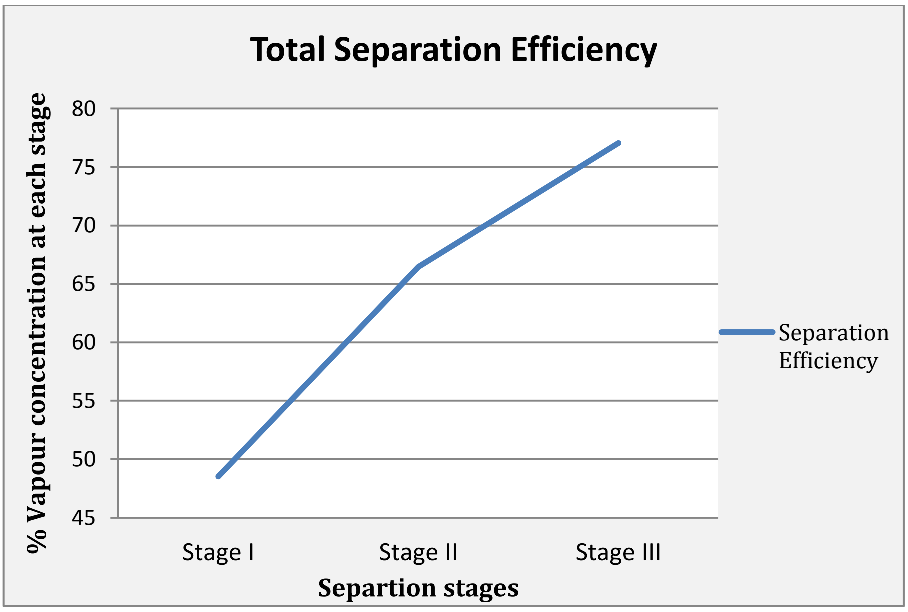

Figure 5.3-2: The vapour-liquid separation efficiency of flash stages (Case-I)

The graphical trend depicts that overall process separation efficiency (based on mass flow rates) increases consistently at each stage though the individual flash units may not be completely efficient. After the final stage, the total efficiency reached is around 80%. Since this high figure was not possible with the single stage, two more stages had to be installed in order to accomplish the process objective.

5.3.1.3 Case Studies and Sensitivity Analysis

In the process, target parameter is the heating value which is to be reduced at optimum yield. The heating value would descend only when higher hydrocarbons (LPG) will be striped of the LNG stream. Removal of these compounds would consequently increase the methane concentration in the stream. Therefore, the methane quantity (or purity) in the natural gas composition will keep on increasing steadily with the decreasing concentration of other hydrocarbons. In other words, the heating value will decrease as the methane content (or concentration) of natural gas blend increases. This fact clearly implies that the methane content of end product should be maximal if a reduction in heating value is desired.

Both parameters, the methane content, and hence the heating value, are greatly affected by the extraction rate of LPG and vapour-liquid separation (particularly in 1st stage). Therefore, the impact of variation of the latter on the former was investigated by performing case studies in HYSYS. From case study 1 and 3, the related trends have been generated, as shown in Figure 5.3-3 and Figure 5.3-4. The effective variables include

- TEE-100 – Flow Ratio (LPG extraction flow ratio)
- q_LNG – Vapour Fraction (Vapour fraction at 1st separator V-101)

The changing effect of above factors were observed on

- NG_pipeline – Molar Flow (Yield at the outlet)
- Phase Comp Mole Frac (Overall-Methane) (i.e., the methane content at outlet stream)

The q_LNG has been selected, since it is principal heat-exchanger and consumes the maximum energy in the process; therefore its behavior is of prime importance.

Since a maximum of two independent variables can be plotted, so the number of states should be limited, and solution time can be minimized in HYSYS by selecting only two independent variable per case-study.

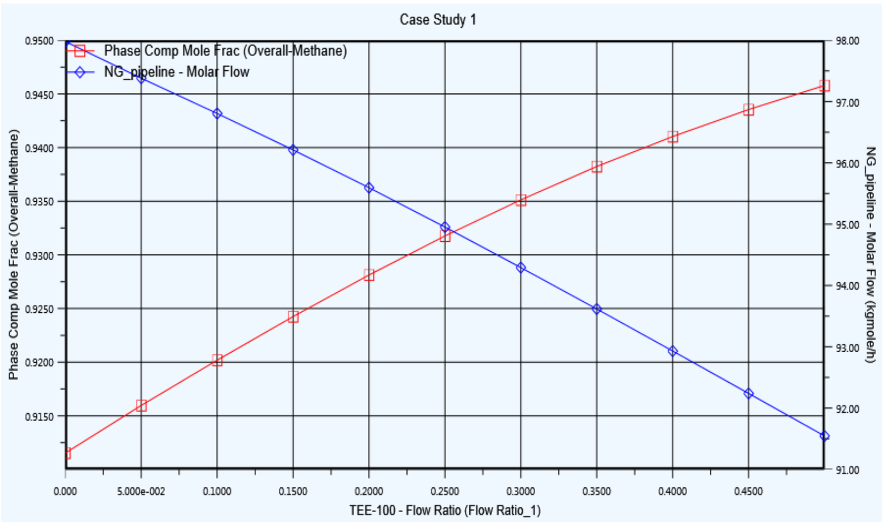

Figure 5.3-3: Impact of variance of LPG extraction rate on yield and methane content in outlet stream NG_pipeline (Case-I)

The trend in Figure 5.3-3 (case study 1) elaborates that natural gas yield decreases linearly, while on the contrary, methane content increases with the increase in quantity of extracted LPG. Nevertheless, outlet methane content changes more rapidly than the yield, implying that methane content is more sensitive to change in the LPG extraction rate.

However, Figure 5.3-4 (casestudy-3) portrays that natural gas yield increases with increase in vapour fraction (or vapour concentration) at 1st separator V-101, whereas methane content shows a decreasing trend with increase in it. Moreover, yield has steeper rise than dropping trend of methane content, which indicates more sensitivity of yield to vapour fraction change at the separator. Data of casestudy1 and 3 are attached in Appendix-14 and 15.

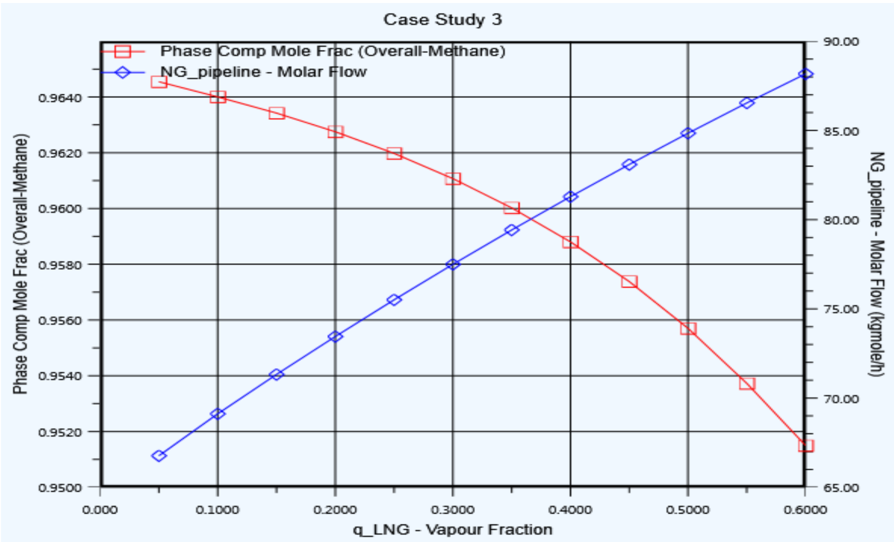

Figure 5.3-4: Effect of changing vapour fraction at 1st separator on yield and methane content at outlet stream NG_pipeline (Case-I)

5.3.1.4 Optimization

The simulation target was to achieve the reduced heating value with the highest mole fraction of methane in the natural gas obtained at the end, for injection to the grid, at an optimum yield. For the purpose, 3 case-studies were carried out by variation of several variables (Case study 1 and 3 explained above in Section 5.3.1.3). In case study 2, the vapour fraction for feed to each separation stage q_LNG, q1_LNG and q2_LNG (at the three heaters q, q1 and q2) are considered for analysis to get their optimal value by varying them simultaneously with the LPG flow ratio, the yield and methane content. 10000 simulations were performed by the system, and these 10000 data points were analyzed for the optimization. The following optimum values were finalized (Table 20).

Table 20: Values of the parameters varied for optimization in Case-I

Parameter	Quantity
q vapour fraction	0.45
q1 vapour fraction	0.3
q2 vapour fraction	0.25
LPG flow ratio	0.5
Molar fraction of methane	0.9575
Molar flow of natural gas	0.8307

Using these optimized values in the simulation, below-mentioned (Table 21) properties of end product, gasified natural gas (stream NG_pipeline) were found.

Table 21: Composition and quality of end-product for Case-I

Component	Unit	Quantity
Methane	mol%	95.75
Ethane	mol%	3.28
Propane	mol%	0.45
n-Butane	mol%	0.06
Nitrogen	mol%	0.47
Yield (molar flow)	%	83.07
Lower heating value	MJ/m^3	36.94
Methane number		88.53

The methane number has been calculated by GRI procedure using MON linear correlation method. The following mathematical relations were utilized.

$$MN = 1.445\, MON - 103.42$$

$$MON = 137.78\, C_1 + 29.948\, C_2 - 18.193\, C_3 - 167.062\, C_4 + 181.233\, CO_2 + 26.994\, N_2$$

where

MN is methane number
MON is motor octane number
C_1 is the mole fraction of methane in natural gas blend
C_2 is the mole fraction of ethane in natural gas blend
C_3 is the mole fraction of propane in natural gas blend
C_4 is the mole fraction of butane in natural gas blend
CO_2 is the mole fraction of carbon dioxide in natural gas blend
N_2 is the mole fraction of nitrogen in natural gas blend

Detailed stream data of Case-I, including compositions, heat flows and unit operations is annexed in Appendix-16.

5.3.1.5 Material & Energy Balance

Mass and energy balances of the entire process for total input and output have been calculated. On the basis of Aspen HYSYS model, the material and energy balances are given in Table 22 and Table 23 respectively.

Table 22: Material Balance for Case-I

Unit	**Material in**		**Material out**	
	Stream	Flow	Stream	Flow
kgmole/h	LNG_Feed	100	NG_pipeline	83.07
kg/h		1803		1388
kgmole/h			L_cond	0.0586
kg/h				1.276
kgmole/h			Extract_LPG	16.87
kg/h				413.3
kgmole/h	**Total**	**100**	=	**100** (± 0.001%)
kg/h		**1803**	=	**1803** (± 0.02%)

The process does not generate any energy, since no internal chemical reaction occurs at any stage of the process.

Table 23: Energy Balance for Case-I

Unit	Energy in		Energy Generation	Energy out	
	Stream	Flow		Stream	Flow
kJ/h	LNG_Feed	-9.252e+006	0	NG_pipeline	-6.685e+006
kJ/h	Q_press	2.306e+004	0	Extract_LPG	-1.633e+006
kJ/h	Q	7.592e+005	0	L_cond	-5433
kJ/h	Q1	8.666e+004	0	Q_bog	-795.2
kJ/h	Q2	5.975e+004	0		
kJ/h	**Total**	**-8.32e+006**	**0**	=	**-8.32e+006**
kW		**-2.31e+003**	**0**	=	**-2.31e+003**

Energy from the Extracted LPG

The higher hydrocarbons removed from the LNG stream can be used to compensate process energy according to the calculation performed in Table 24 .

Table 24: Energy calculation of extracted LPG in Case-I

Parameter	kW	kgmole/h	kg/h
Total energy consumption in the process as per process conditions	257.755		
Total LPG extracted	5515.55	16.87	413.3
LPG required as fuel to get process energy		0.788	
Balance of LPG	5257.798	16.082	393.84

As per the above computation, out of total 16.87 kgmole/h of LPG produced, 0.788 kgmole/h can be used as fuel to supply heat/ energy to the regasification process, and the balance16.082 kgmole/h or 393.84 kg/h LPG is available for storage or sale to market. It may be utilized in power production as well, having 5.26 megawatt capacity.

5.3.2 Case-II (Nitrogen Ballasting)

The de-richment of the received LNG can be accomplished by injecting nitrogen in the LNG stream, which is known as nitrogen ballasting. Compared to Case-I, the major change in process configuration is the exclusion of vapour-liquid separation stages, and existence of nitrogen mixer at the BOG-handling step. Addition of nitrogen has dilution effect in the natural gas blend, thereby reducing the heating value; the same is the principle of operation for this method.

5.3.2.1 Process Description

For this process, it is assumed here that nitrogen is produced at 8 bar pressure (as per industry practice) (GL Noble Denton, Pöyry Management Consulting, 2011) by an air separation unit (ASU) on the plant site. Typically, the nitrogen is added in the LNG boil-off gas (BOG) before re-condenser. This nitrogen is then absorbed by the LNG along with BOG, and is pumped to the pipeline injection pressure (45 bar for this case) prior to regasification system (vapourizers) and final entry to the gas grid.

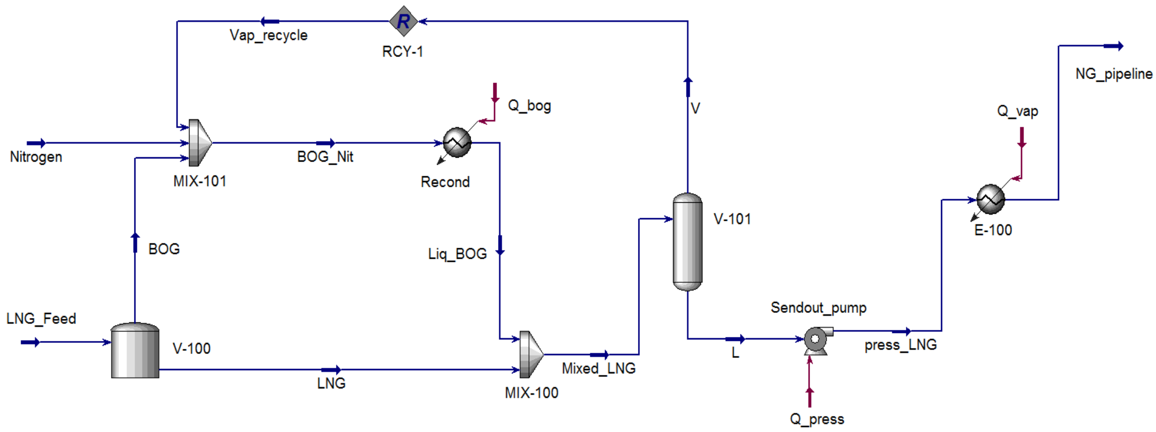

Figure 5.3-5: HYSYS simulation diagram of LNG quality control by N_2 injection (Case-II)

As depicted by the simulation scheme displayed in Figure 5.3-5, feed stream LNG_Feed enters the storage tank V-100 at temperature of -161.7°C and 101.3 kPa pressure; the boil-off gas, BOG, leaves the tank at same temperature and pressure to BOG handling system. The nitrogen is mixed with incoming BOG at this point at 8 bar pressure and -172.9 °C. The mixture of BOG and nitrogen are condensed in the re-condenser Recond so that they could be mixed at MIX-100 with main (liquid) LNG stream “LNG” going to the suction header of sendout pump at same pressure and temperature as that of BOG. At this mixer MIX-100, the methane composition of stream LNG is altered from 90.10% to 82.28% as it is blended with nitrogen-rich liquid stream Liq_BOG. The heating value of LNG is reduced actually at this step.

A vapour-liquid separator V-101has been installed before Sendout_pump, since the stream Mixed_LNG shows a vapour fraction of 0.0394 at flow rate of 110.6 kgmole/h, which means it contains small amount of vapours, which denotes that it is not thermodynamically possible to have stream Mixed_LNG as liquid under these conditions, therefore, a flash separator is needed to strip the vapour part, to avoid cavitation in the pump. The separator V-101 flashes out the vapours, at -176.5°C temperature and 101.3 kPa pressure, and the liquid stream L from its bottom goes to the pump at flow rate of 106.2 kgmole/h. The separated vapour stream V (around 4% of Mixed_LNG) flowing at the rate of 4.352 kgmole/h, is recycled back to the BOG_Nit stream at the nitrogen mixing point MIX-101 at same pressure, temperature conditions as liquid stream L. The sendout pump raises the pressure of L to 4500 kPa (45 bar), however, temperature increase is minute i.e., around 2°C. This high pressure pump discharge-stream press_LNG then enters the vapourizer or heat exchanger E-100 for actual regasification at flow rate of 106.2 kgmole/h. The final stream NG_pipeline is obtained at temperature and pressure of -28.45°Cand 4500 kPa.

It was observed that 8 bar injection pressure of nitrogen have no effect on the end product. The detailed stream, composition and energy data of simulation is appended in Appendix-17. Final product features are shown in Table 25.

Table 25: Composition and quality of end-product for Case-II

Component	Unit	Quantity
Methane	mol%	84.83
Ethane	mol%	5.84
Propane	mol%	2.17
n-Butane	mol%	0.94
Nitrogen	mol%	6.22
Yield (molar flow)	%	100
Lower heating value	MJ/m^3	37.29
Methane number		67.59

5.3.2.1 Material & Energy Balance

The following Table 26 and Table 27 represent the material and energy balance data of the process, which are calculated on the process, as a whole, for total input and output as per Aspen HYSYS model.

Table 26: Material Balance for Case-II

Unit	Material in		Material out	
	Stream	Flow	Stream	Flow
kgmole/h	LNG_Feed	100	NG_pipeline	106.2
kg/h		1803		1977
kgmole/h	Nitrogen	6.2		
kg/h		173.7		
kgmole/h	**Total**	**106.2**	=	**106.2**
kg/h		**1976.7**	=	**1976.7** (± 0.01%)

Table 27: Energy Balance for Case-II

Unit	Energy in		Energy Generation	Energy out	
	Stream	Flow		Stream	Flow
kJ/h	LNG_Feed	-9.252e+006	0	NG_pipeline	-7.994e+006
kJ/h	Nitrogen	-3.763e+004	0	Q_bog	-1.139e+005
kJ/h	Q_press	2.322e+004	0		
kJ/h	Q_vap	1.386e+006	0		
kJ/h	**Total**	**-7.88e+006**	**0**	=	**-7.88e+006** (± 2.8%)
kW		**-2.19e+003**	**0**	=	**-2.19e+003** (± 2.8%)

No energy is actually generated in the process, since it does not involve any chemical change, but only phase change.

5.3.3 Case-III (CO_2 Injection)

The heating value reduction by addition of carbon dioxide to the LNG is named as CO_2 Injection. This process utilizes the same approach and operating principle for LNG de-richment as that by previous method, but carbon dioxide is used instead of nitrogen for de-richment of the natural gas. The difference in process configuration is the elimination of flash separator before the high pressure sendout pump, since no vapour fraction is present in the mixed LNG-BOG stream prior to the pump.

5.3.3.1 Process Description

The CO_2 is assumed to be available at 2 bar injectable pressure. CO2 is mixed with BOG stream in vapour phase at temperature of -161.7°C and 101.3 kPa pressure. The mixing takes place at same pressure but at -78.76 °C temperature. The stream BOG_CO2 passes through recondenser for a complete phase change to liquid, and combines with stream LNG which is at the same temperature and pressure as that of the tank. At this point, the composition of LNG greatly transforms from a methane content of 90.1 % to 84.88%, because of mingling with CO_2-rich stream Liq_BOG. This joint stream Mixed_LNG subsequently connects to the sendout pump which raises its pressure from atmospheric to the 45 bar. With a flow rate of 106.2 kgmole/h, the stream press_LNG undergoes another phase change when it is heated in vapourizer E-100, which raises its temperature from -175.2°C to -27.46°C and pressure to 45 bar, but does not affect its flow rate. The stream NG_pipeline is then ready to be injected to gas grid. Simulation scheme of the process is represented by Figure 5.3-6.

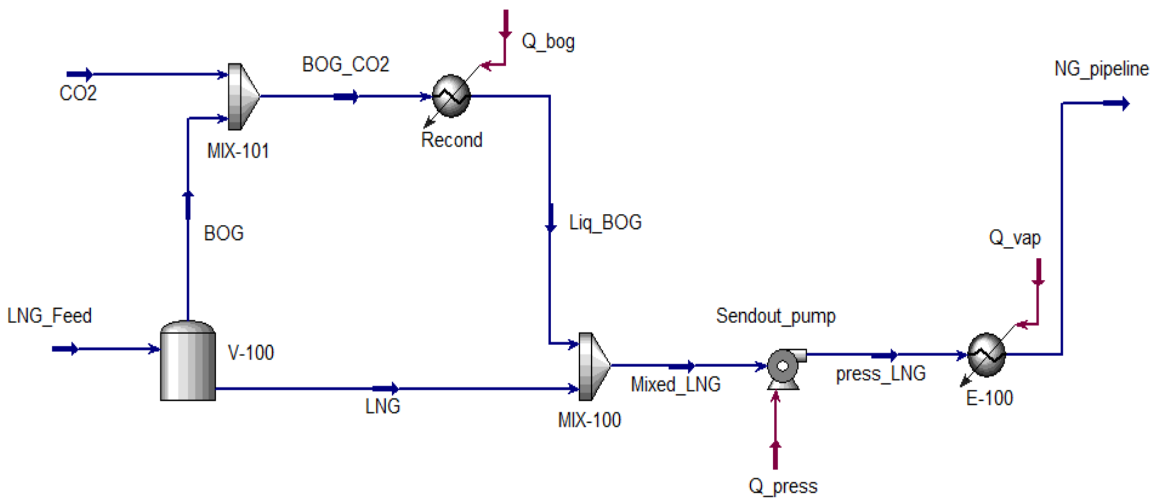

Figure 5.3-6: HYSYS scheme for LNG quality control by CO_2 injection (Case-III)

The quality parameters of the end product are listed in Table 28, while detailed stream, composition and energy data of simulation is provided in Appendix-18.

Table 28: Composition and quality of end-product for Case-III

Component	Unit	Quantity
Methane	mol%	84.88
Ethane	mol%	5.84
Propane	mol%	2.17
n-Butane	mol%	0.94
Nitrogen	mol%	0.38
CO_2	mol%	5.80
Yield (molar flow)	%	100
Lower heating value	MJ/m^3	37.33
Methane number		80.57

5.3.3.2 Material & Energy Balance

The material and energy balance are considered around the whole process for total incoming and outgoing species. They are represented by the data listed in Table 29 and Table 30.

Table 29: Material Balance for Case-III

Unit	Material in		Material out	
	Stream	Flow	Stream	Flow
kgmole/h	LNG_Feed	100	NG_pipeline	106.2
kg/h		1803		2074
kgmole/h	CO2	6.155		
kg/h		270.9		
kgmole/h	**Total**	**106.155**	=	**106.155** ($\pm$ 0.04%)
kg/h		**2073.9**	=	**2073.9** ($\pm$ 0.005%)

Table 30: Energy Balance for Case-III

Unit	Energy in		Energy Generation	Energy out	
	Stream	Flow		Stream	Flow
kJ/h	LNG_Feed	-9.252e+006	0	NG_pipeline	-1.043e+007
kJ/h	CO2	-2.447e+006	0	Q_bog	-2.094e+005
kJ/h	Q_press	2.288e+004	0		
kJ/h	Q_vap	1.453e+006	0		
kJ/h	**Total**	**-1.02e+007**	**0**	=	**-1.02e+007** (± 4%)
kW		**-2.84e+003**	**0**	=	**-2.84e+003** (± 4%)

There is no energy generation in this process.

5.4 Evaluation /Comparison of the Cases

As referred to in Section 2.6.1, all the above 3 cases (processes) have mature technologies and are widely utilized in the LNG industry.

LPG recovery and nitrogen ballasting are common at LNG terminals; CO_2 injection is twice more effective than nitrogen in diluting the natural gas (Section 2.6.1). In addition to the basic process of Case-II (nitrogen ballasting), referred by the diagram, there are numerous ancillary equipment and costs involved in the whole procedure. Nitrogen, which is pre-requisite, is produced from atmospheric air and there are several techniques available for nitrogen production:

- cryogenic air separation
- Pressure Swing Adsorption (PSA)
- membrane air separation

Since the large quantity of nitrogen is required for injection, an on-site cryogenic air separation unit would usually be needed. The PSA option is expected to be uncompetitive at high capacities and the membrane option is also not economical since it involves insufficient nitrogen purity at an acceptable price. In order to produce larger amounts of nitrogen, a cryogenic air separation unit (ASU) would be have to be installed to economize the process of LNG de-richment by nitrogen ballasting. The total installed cost of the ASU sized at peak flow along with one-day backup storage facilities is counted in the capital expenditure of nitrogen ballasting plant. For the backup storage, the nitrogen is stored in liquid form, so the cost will also include the liquid nitrogen storage cascade and air vaporizer.

Although, these methods can be compared from variety of angles, the present comparison considers the process feasibility. A statistical comparison of these cases has been carried out by accumulating the relevant data in Table 31.

Table 31: Data comparison of final stream NG_pipeline for all three Cases

Component/ Property	Unit	Case-I (LPG Extraction)	Case-II (N_2 Ballasting)	Case-III (CO_2 Injection)
Methane	mol%	95.75	84.83	84.88
Ethane	mol%	3.28	5.84	5.84
Propane	mol%	0.45	2.17	2.17
n-Butane	mol%	0.06	0.94	0.94
Nitrogen	mol%	0.47	6.22	0.38
CO_2	mol%	0.00	0.00	5.80
Vapour fraction		1.0000	1.0000	1.0000
Temperature	°C	-69.51	-28.45	-27.46
Pressure	kPa	4500	4500	4500
Molar flow	kgmole/h	83.07	106.2	106.2
Mass flow	kg/h	1388	1977	2074
Liquid volume flow	m^3/h	4.543	5.881	5.994
Heat flow	kJ/h	-6.685e+006	-7.994e+006	-1.043e+007
Yield (molar flow)	%	83.07	100	100
Energy consumption	kW	257.75	359.711	351.696
Injection rate	%		6.22	5.8
HHV	MJ/m^3	40.9485	41.2458	41.2824
LHV	MJ/m^3	36.9445	37.2965	37.3296
Wobbe index (lower)	MJ/m^3	48.5885	46.4735	45.3941
Wobbe index (higher)	MJ/m^3	53.8544	51.3945	50.2008
Methane Number (GRI)		88.53	67.59	80.58

According to the above table, from process complexity and yield point of view, CO_2 injection is evidently the simplest, and yielding as compared to others. It is also comparable in energy consumption and product quality. On the other hand, LPG extraction is the most complex, involves many components and unit operations, but produces LPG without much decreasing the methane yield.

The quality defining parameters have been plotted on the graph for each case individually, displayed in Figure 5.4-1.

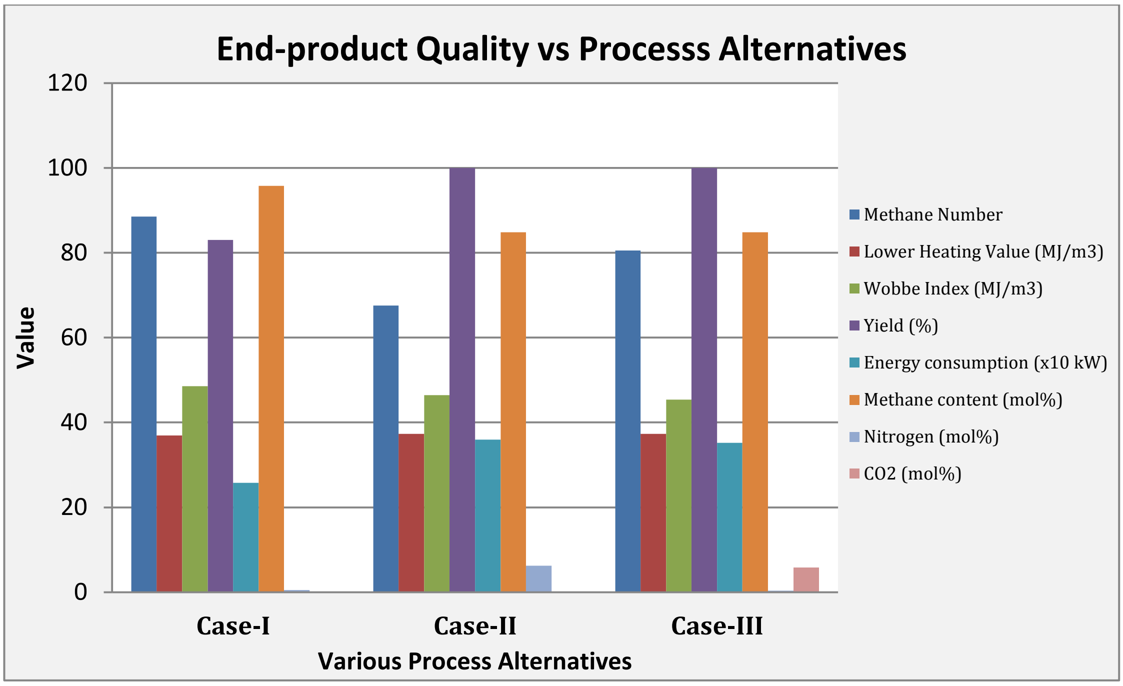

Figure 5.4-1: Visual representation of quality parameters of end product obtained from different process alternatives

As portrayed by the graphical representation (Figure 5.4-1) of end-product quality, Case-II is the most energy intensive process among all three alternatives. The graph shows that for the same value of target parameter LHV, Case-II consumes 359.7 kW and has average yield and smallest methane number, whereas Case-I not only consumes the least energy (257.755 kW), but also generates energy in the form extracted LPG, which is marketable or could be used for power production. Also, it gives highest methane content (95.65%) and methane number, though it gives slightly lower yield compared to other processes.

The yield of Case-I is less than the other two cases, which is because of separating higher hydrocarbons from the feed, whereas Case-II and III add the impurities for dilution of LNG feed and same accumulative amount is resulted in the final product stream NG_pipeline, according to simulation calculation.

In order to select the most feasible process, a selection criteria has been founded in the form of a selection table of all the cases, given hereunder (Table 32).

Table 32: Selection table of the Cases (Points scale 1-10)

Process Alternatives		**Case-I (LPG Extraction)**		**Case-II (N_2 Ballasting)**		**Case-III (CO_2 Injection)**	
Criteria	Weight	Points	Total	Points	Total	Points	Total
Product Quality	8	10	80	6	48	5	40
Environmental friendliness	7	6	42	4	28	2	14
Safety	7	6	42	5	35	4	28
Costs	6	5	30	5	30	7	42
Profitability	6	10	60	4	24	4	24
Product Yield	5	8	40	10	50	10	50
Process conditions	4	6	24	5	20	6	24
Complexity	4	3	12	6	24	8	32
Robustness	3	7	21	8	24	9	27
Raw material availability & cost	2	10	20	4	8	5	10
References	2	10	20	6	12	2	4
Maturity	1	8	8	7	7	6	6
Total	54		399		310		301
Score		**7.25**		**5.636**		**5.47**	

In establishing the process selection criteria, product quality, environment and safety have been given topmost notches, since quality control of natural gas is the process intent, and safety and environment are key apprehensions of the industrial world. Other important factors include economics, yield, process conditions, robustness and complexity of process, in that order. Complexity holds priority over raw materials and references (holding the same weightage), since a simple and operator-friendly plant counts more than an old technology, particularly in this case, where raw materials are only the LNG at receiving terminal and common gases nitrogen and CO_2.

Case-I secures top place in quality, profitability, raw material and references groups, because of producing 95% methane purity and a high market value by-product (LPG). It also does not need additional raw material, unlike Case-I and II which need nitrogen and CO_2, to process LNG, and it is a time-tested technology. Case-II is low in quality category as it produces impure (nitrogen mixed) natural gas, but not lower than Case-III which also has same condition, but has lesser grade due to stricter CO_2 limits in the gas. Case-II, as discussed above, is high on cost, due to involvement of nitrogen liquefaction equipment and compressors, such that it comes almost in line with Case-I, which has more unit operations and vessels. Case-III, on the other hand, has most economical process, since it does not require large compressors or many tanks.

Case-I achieves 6 points each for equal-weightage classes, environmental friendliness and safety, which is still better than the other two cases. Its average marks are due to effluents and emission involved in its sub-processes, such as LPG handling, storage and dispatching facilities. These activities have several health and safety risks, including hydrocarbon emissions, LPG handling hazards, fire hazards, health risks, and personnel injuries. Case-II and III secure 4 and 2 points respectively in this category, as they also have suchlike effects. CO_2 injection has environmental implications, and it is strongly regulated in European natural gas networks. This trend is therefore discouraged and the Finnish gas allows less than 2.5% CO_2 (as per Table 11, Section 3.2.3), while the above process injects 5.8%. Apart from this constraint, the process is the simple with safe operating and working conditions. Compared to 5.8% CO_2 addition, 6.22 % nitrogen is injected in nitrogen ballasting, for 100 kgmole/h of LNG feed rate. Finnish national grid limit of nitrogen is 3% CO_2 (as per Table 11, Section 3.2.3) at maximum. Thus, these methods are on the negative side by environmental questions such as global warming, GHG emissions and climate change.

Case-I has lowest rank in complexity and robustness than other cases, for reasons of possessing large process set up containing 3-stage separation operation and ancillary equipment such as heat exchangers, and LPG handling facilities, which may increase the probability of plant issues. Other processes are uncomplicated and Case-III is the simplest, which just injects CO_2 in the LNG stream and obtains natural gas straight after vapourizer. This is one reason for its high rank in categories of costs, process conditions, robustness, and to some extent, profitability.

Case-II and III are technically mature technologies as illustrated in Section 2.6.1; however, number of CO_2 mixing plants is decreasing on environmental grounds. Both of them are yielding as they give 100% natural gas yield, and there are no losses, whereas Case-I has lower yield since it splits the feed and yields a co-product.

As per the analysis of various aspects and position of relevant score from Table 32, Case-I clearly ranks highest among all competing processes under consideration, thereby declaring LPG Extraction, more advantageous than others, primarily because of its ability to generate profits and sellable energy.

Case-I is attractive also because of the fact that by using refrigeration inherent in the cold LNG, high quality NGL/ LPG marketable product can be obtained without any added refrigeration or external compression power.

5.5 Process Improvement

The process described in Case-I (LPG extraction) can be improved from process point of view.

The energy efficiency of the process could be increased by performing "heat integration". For instance, the recondenser needs cold energy to convert the boil-off gas back to liquid, so the cold of LNG itself can be utilized for this purpose by circulating the LNG stream in the recondenser. The use of this "free" refrigeration in the LNG to extract the liquids also decreases the amount of external heat (energy/fuel consumption) required to vaporize the LNG, thus reducing the operating cost of the LNG terminal. Therefore, not only the process intent is achieved but also a saleable co-product is available for generating additional revenues.

Referring to the simulation diagram of Case-I, in addition to the normal recycle stream Recyc of LPG, a minute quantity of liquid condensate is present in the final natural gas stream mix_NG. This liquid L-cond can also be recycled, thereby increasing the process yield. In the process, an increase in the recycle stream would raise the product flow though, yet it would in turn lower the product purity. Therefore, a compromising point between the quantity and quality would define the process orientation. Accordingly, the three-staged configuration can be changed to single or double-staged depending on the prioritized yield level of natural gas for grid injection.

The final pipeline injectable gas and the extracted LPG are at low temperatures of -69.51°C and -61.88°C respectively, which can be used in many cold applications.

As described in Chapter 2, Submerged Combustion Vapourizers (SCVs) are typically used in cold climate conditions. The LPG produced can also be used as fuel in these vapourizers to heat the LNG at first separation stage, which has the highest energy consumption of 211 kW. For next stages where power requirement is low (24 kW and 16.6 kW), ambient air vapourizers (AAVs) can be utilized which are plate-fin heat exchangers using ambient air temperature to vapourize the LNG.

6. Discussion and Recommendations

LNG chain is in the emerging phase and many new applications and equipment, such as LNG liquid fuel engines, are evolving in this realm with their respective value addition and challenges.

The Finnish natural gas grid is based on high quality gas, which is the reason of its extraordinary quality requirement. At current state of affairs, Gasum grid stays demanding with the uppermost specification in context of methane number. The grid though serves all types of applications, majority uses it for heating purposes, and methane number (MN)-cautious customers are few. Therefore, the engine sector practically defines the quality of the fuel natural gas, as engine efficiency and performance is considerably affected by quality of fuel. So they have stricter criteria and are more sensitive to properties such as MN and Wobbe Index, even though MN is chiefly the issue of larger engines. It is worth-mentioning that high MN required by vehicle manufacturers is meant for full-rated capacity and optimum performance of the engine. Nevertheless, the engine would still work even with very low methane number but at lower efficiency, and with almost negligible efficiency loss for smaller (+/- 5%) variation in this quality parameter. Thus, the marine engines, gas/ power turbines, gas power-generators, and road transport are the preferred applications in delineating/outlining the quality specifications of natural gas and the imported LNG in Finland.

On second priority is the industry which uses natural gas as feedstock, for example Neste (uses it for hydrogenation for various petrochemicals production), Kemira (employs natural gas to produce water-gas $CO+H_2$ for methanoic acid as end product), consequently they need more carbon in natural gas or higher hydrocarbons to maintain CO/H_2 ratio. Meanwhile, there is an increasing demand from potential customers (e.g., Kemira and Norilsk Nickel) who intend to use natural gas as feedstock for hydrogen production (by steam reforming or thermal cracking of hydrocarbons); they seek a natural gas with high hydrogen content (hydrogen to carbon ratio) even in the composite form.

Most of the general industry in Finland utilizes natural gas as a fuel for ovens, burners, dryers, melting, boilers, and furnaces, so they are more interested in energy-content (kW) of the fuel or higher hydrocarbons in natural gas (and not in other parameters such as MN, Wobbe index), hence natural gas quality is not under their main consideration. Some of them currently use viscous (2000 centistoke), extra-heavy Fuel Oil ("erp" in Finnish) for combustion applications.

In that way, Finnish natural gas market can be categorized into two broad classes, the engine fuel and the direct combustion or burning fuel. Therefore, it could be proposed that two types of storages are maintained for each of the segment. The quality-oriented engine sector should be provided with special quality, high MN gas and rest of the consumers should access the normal one. The priority sector can be defined by the share of the annual gas sale, which could be obtained from sales statistics.

Nonetheless, this would further necessitate an infrastructure, as both the qualities would definitely not be injected to the same grid, and one of them would have to be marketed and transported separately, possibly though trucking, which will make LNG an expensive merchandise. As a whole, for joint fuel system, methane number remains the limiting factor in selecting the natural gas quality from LNG variety available world over.

Additionally, it is established that tempering with the LNG quality to increase Wobbe Index of the sendout causes an increase in CO and NOx emissions at end-use combustion, thereby restraining the scope of LNG enrichment.

Finally, as per Finnish market requirement and the prevailing grid conditions, out of 27 global LNG sources, the number of feasible sources though remains 3, yet this number can be increased to 7 by compromising the MN demand of land traffic sector (which has tiny gas market share), and to 11 if the maximum permissible limits for natural gas heating value are increased by approximately 3%. LNG from rest of the producers can be viable with additional processing at the import terminal, for instance, nitrogen ballasting. Furthermore, Zeebrugge, Gate and Klaipeda LNG re-export terminals cover most Finnish market demand, and thus have the potential to be intermediate LNG import origin for Finland.

Among the three LNG de-richment methods, LPG Extraction is found to be most attractive based on the comparison of simulated models of these three selective processes evaluated on a criterion mainly influenced by economic and environmental factors.

This thesis establishes the minimum requirement of Finnish natural gas specifications, further work could be directed to determine the maximum or the upper bounds of these specifications to formulate a joint Finnish natural gas standard for future imports of natural gas to Finland. Moreover, the simulation models in this work are at nascent stage, thus possessing vast capacity for improvements in the scale-up and functional results along with the cost-benefit analysis, which requires additional study and research work in this field.

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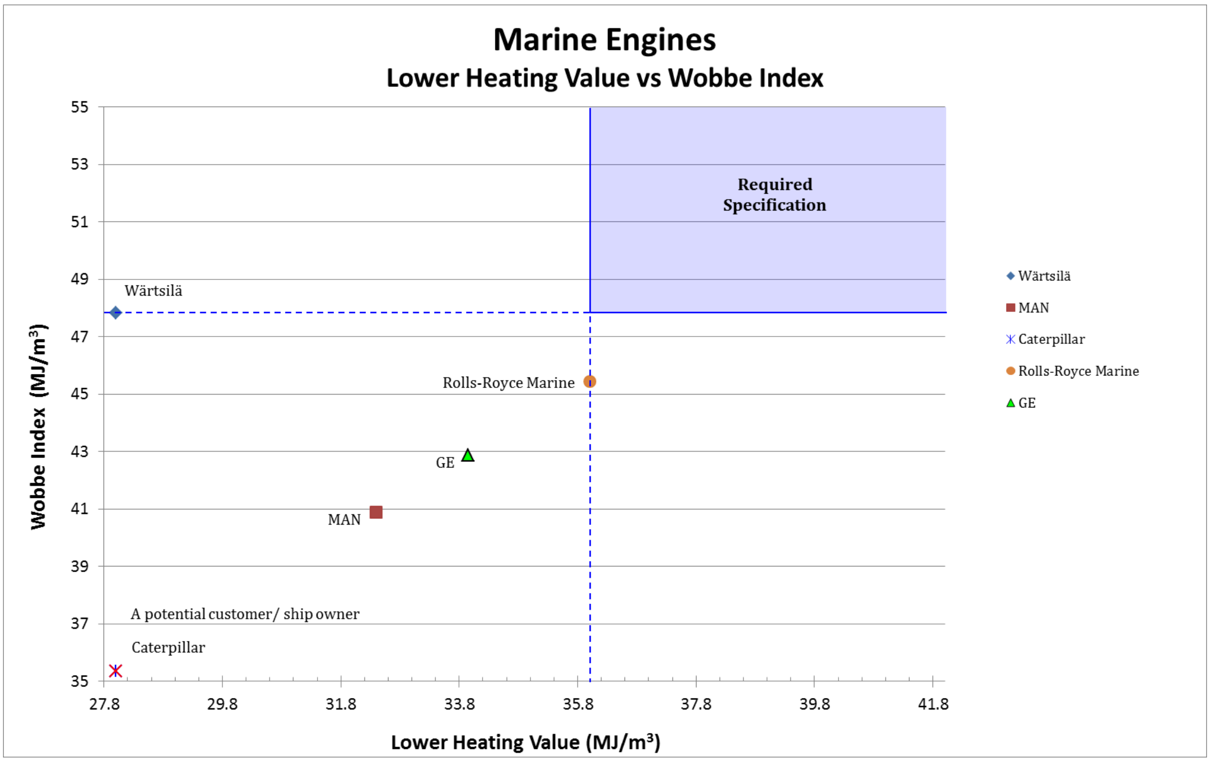
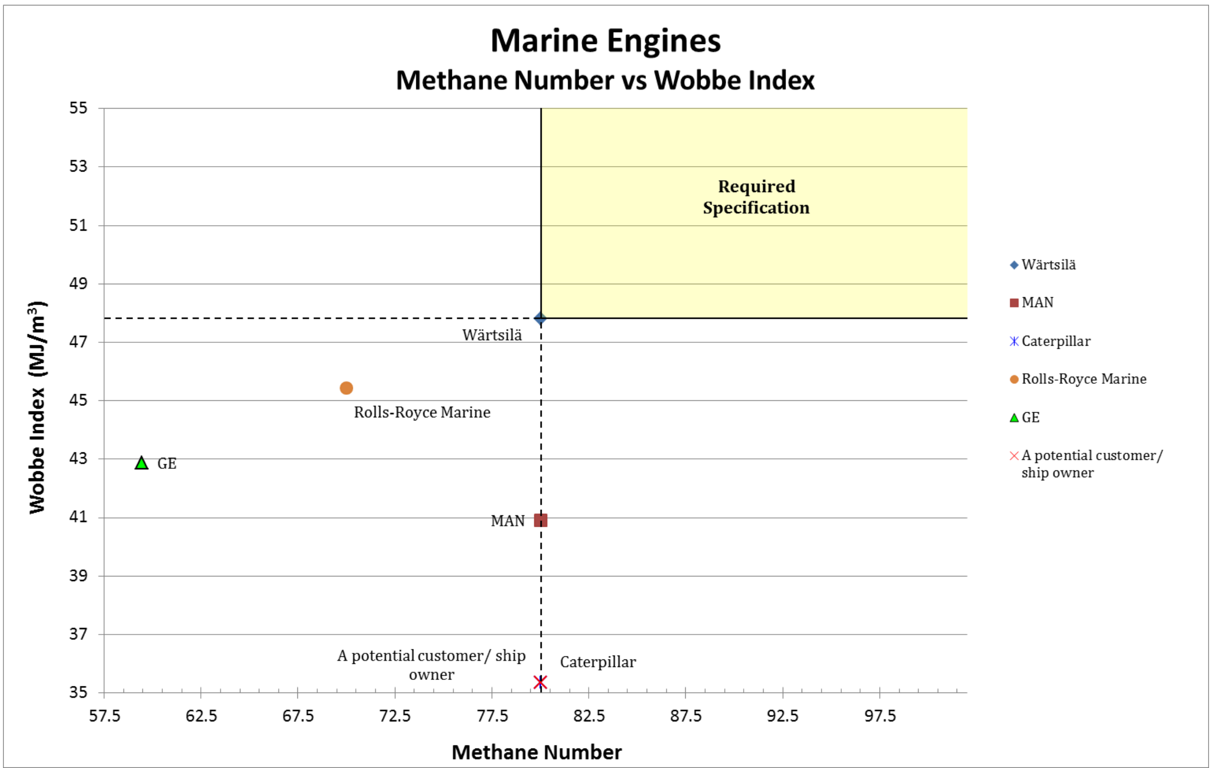
8. Appendices

8.1 Appendix-1

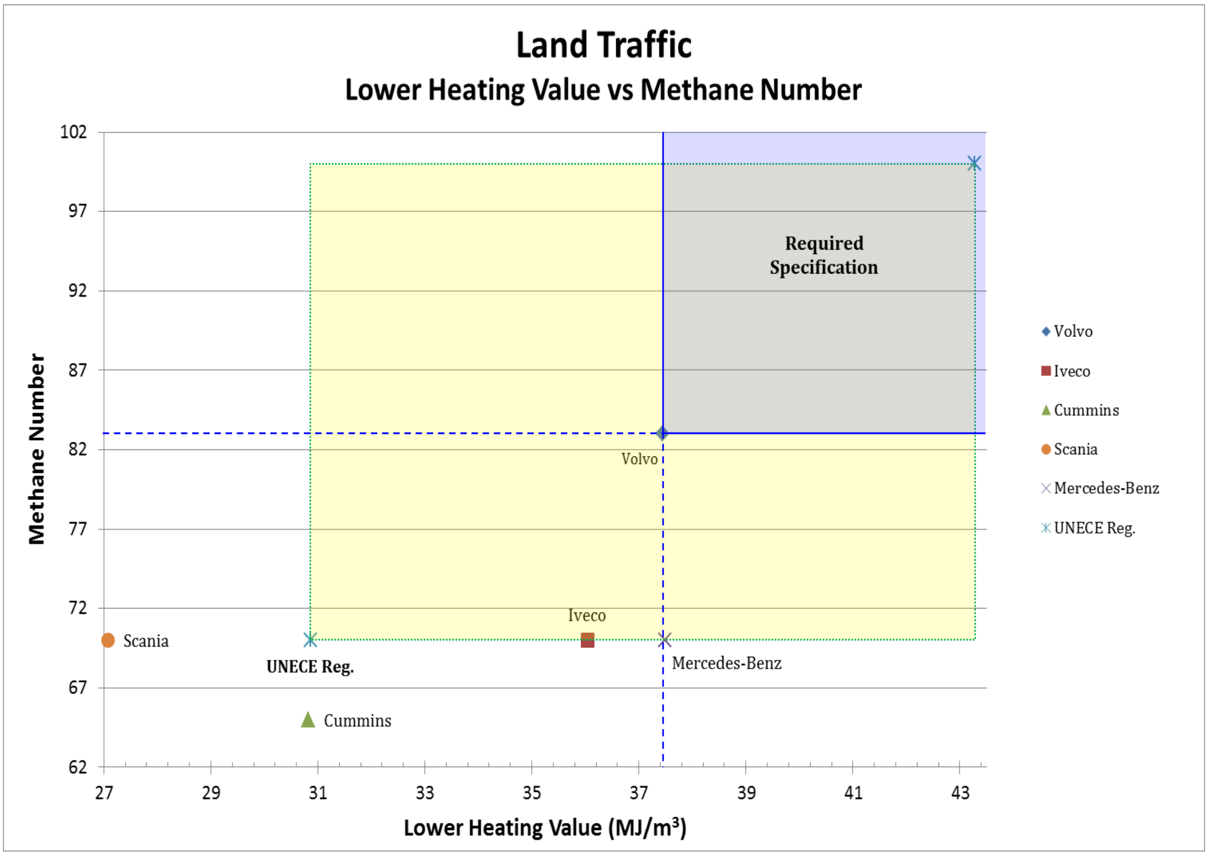
Maps for the Marine Traffic Engines sector

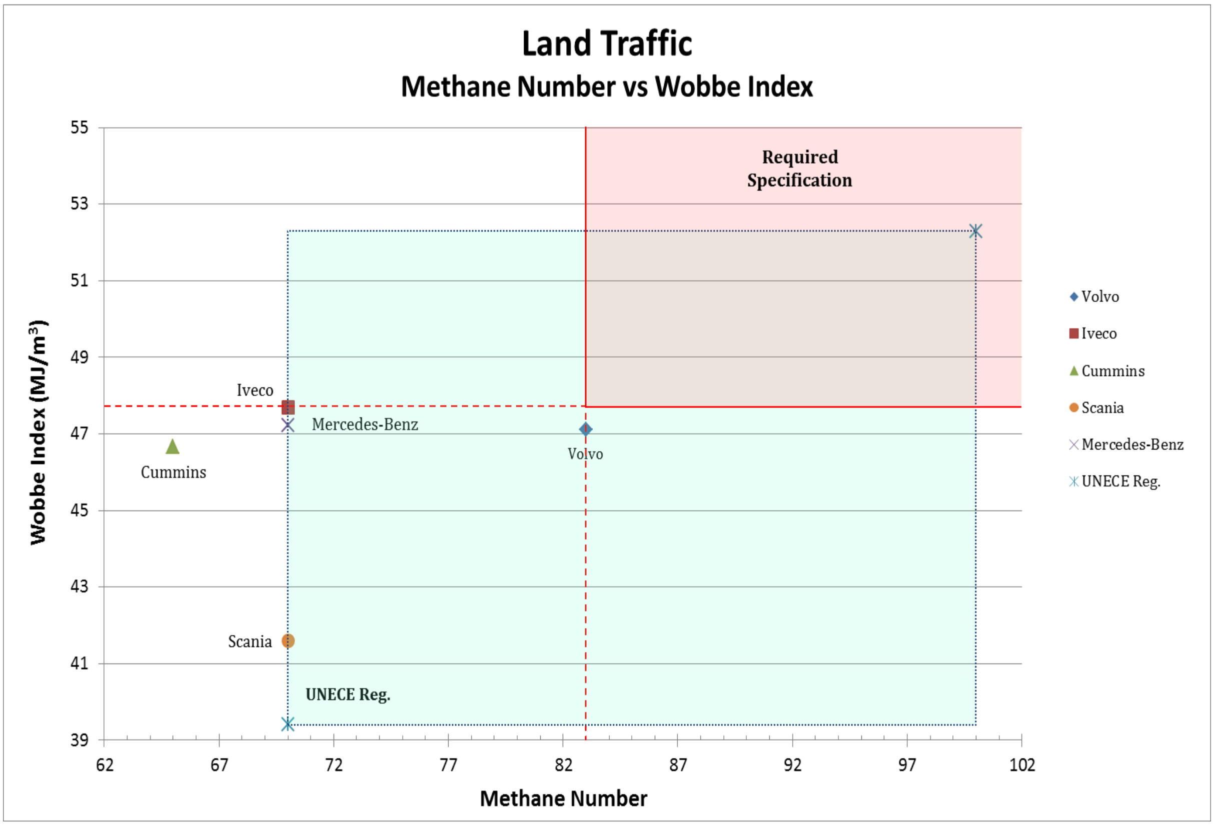




8.2 Appendix-2

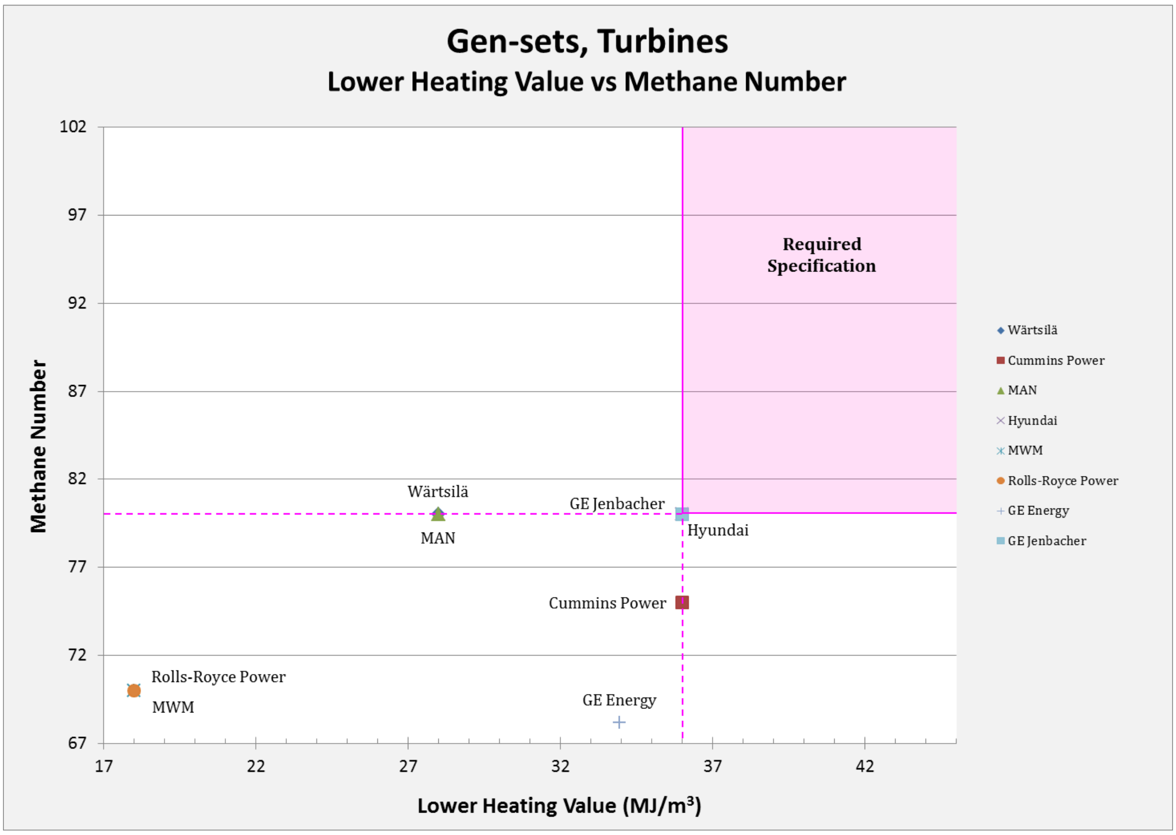
Maps for Land Traffic sector

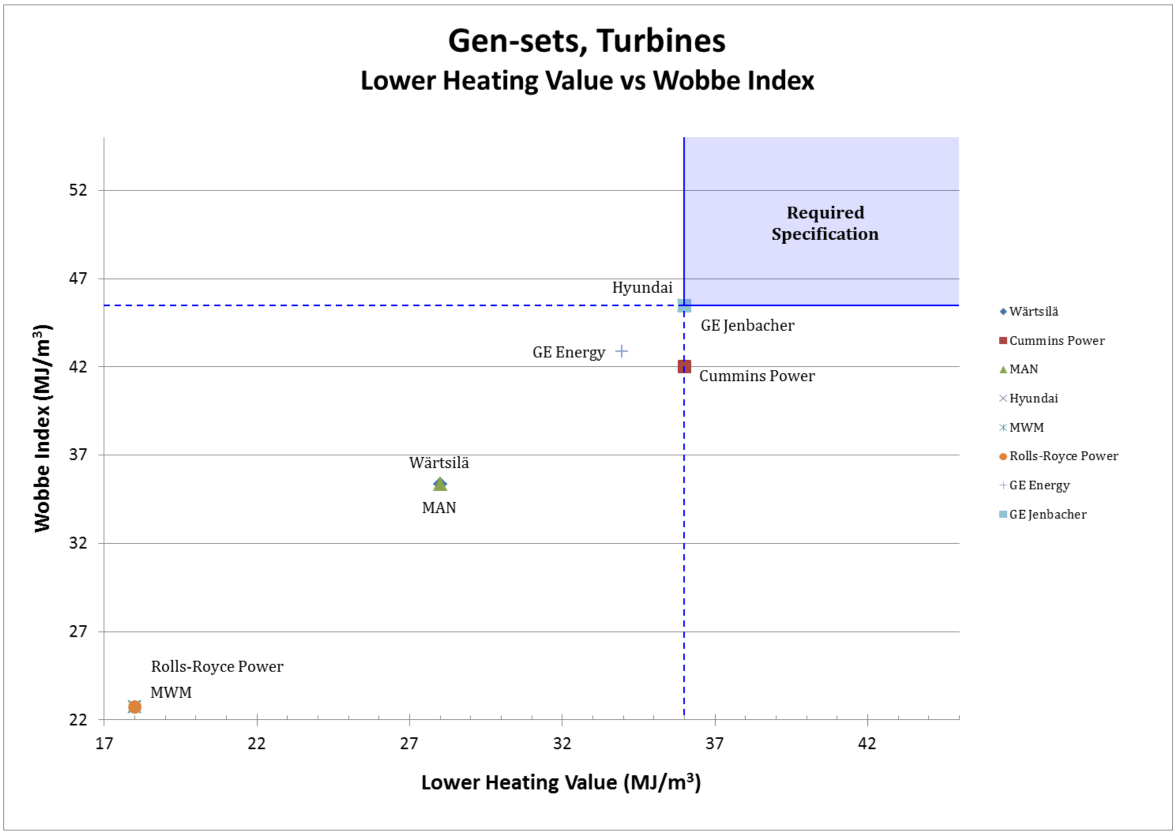




8.3 Appendix-3

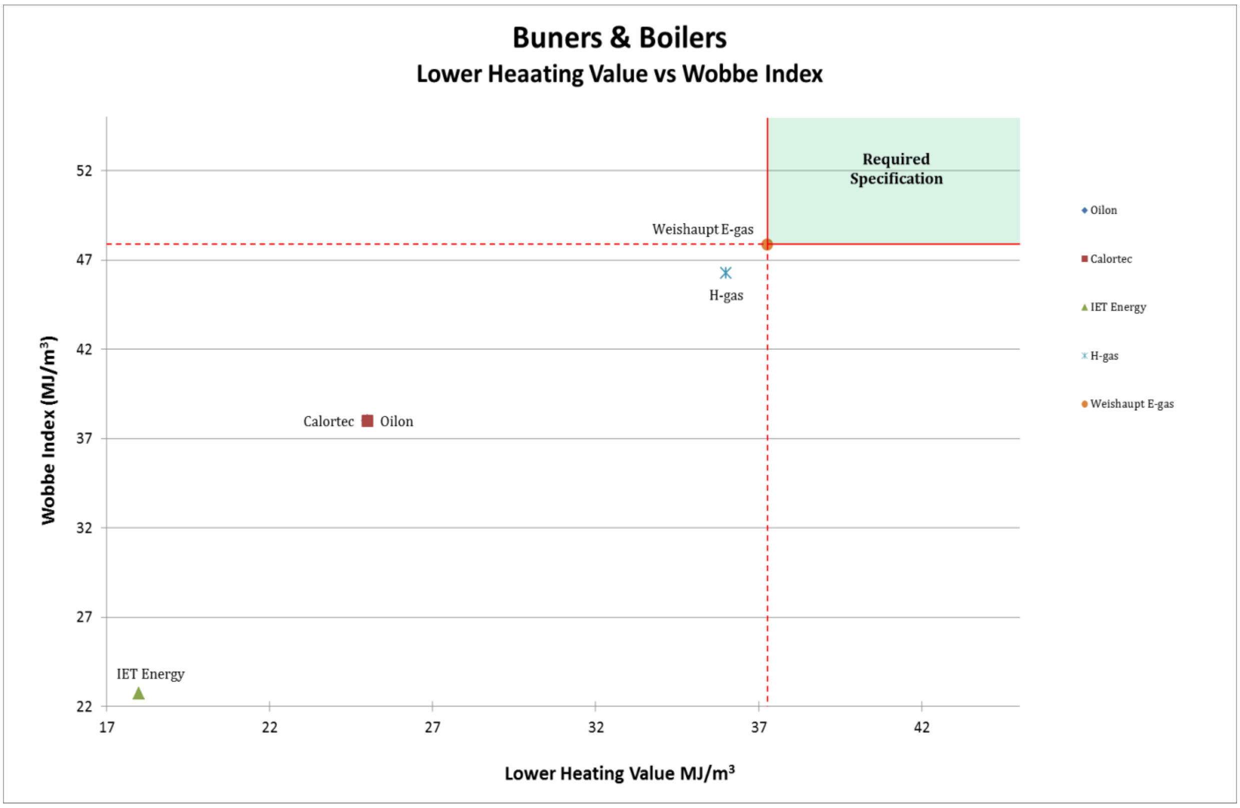
Maps for Gen-sets, Turbines sector

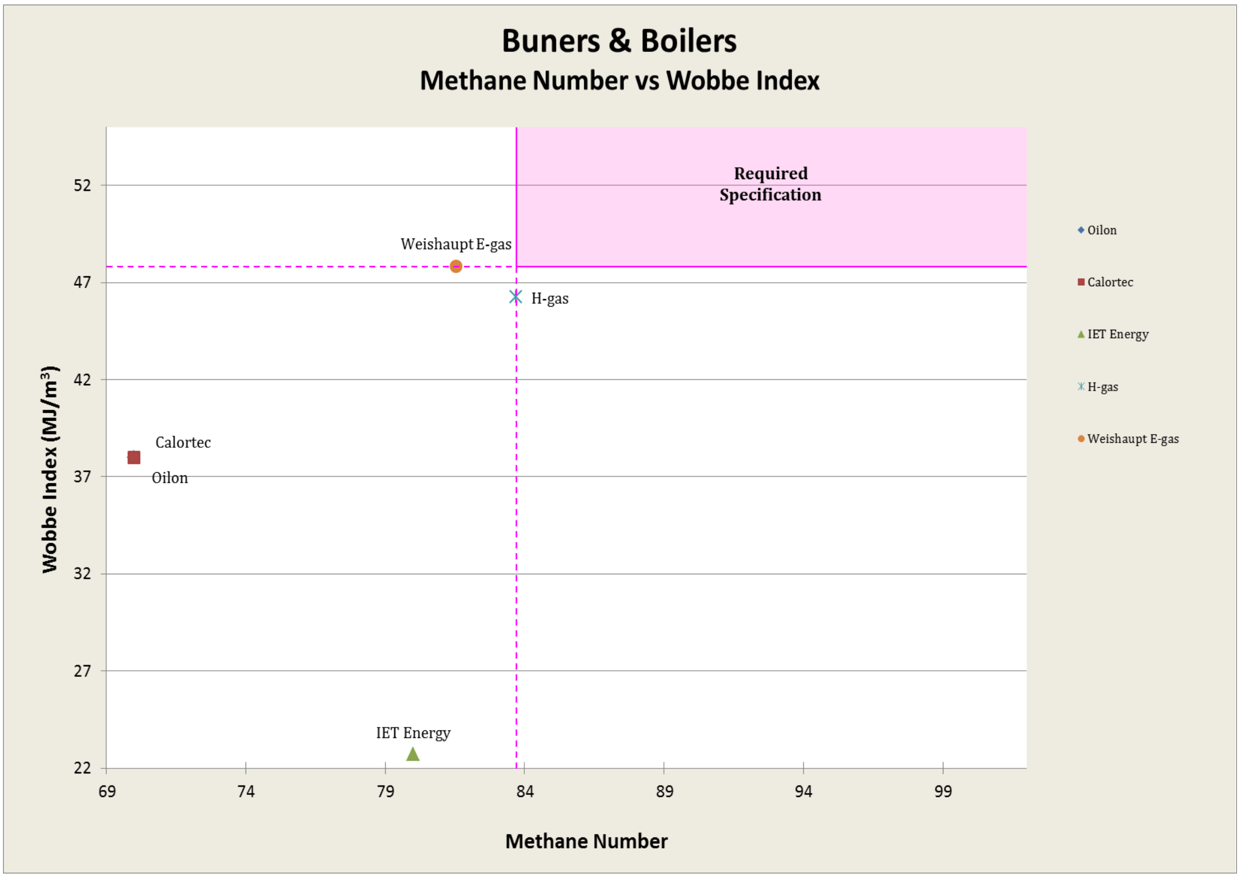




8.4 Appendix-4

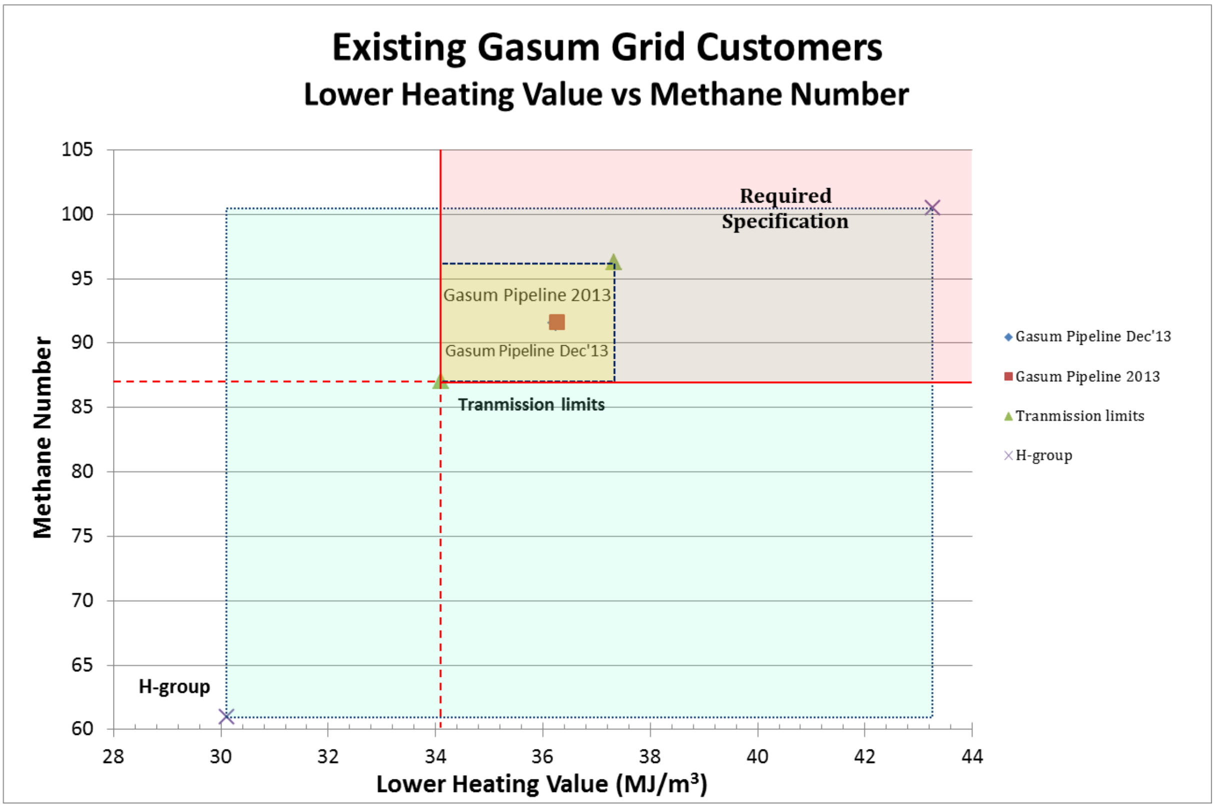
Maps for Burners, Boilers sector

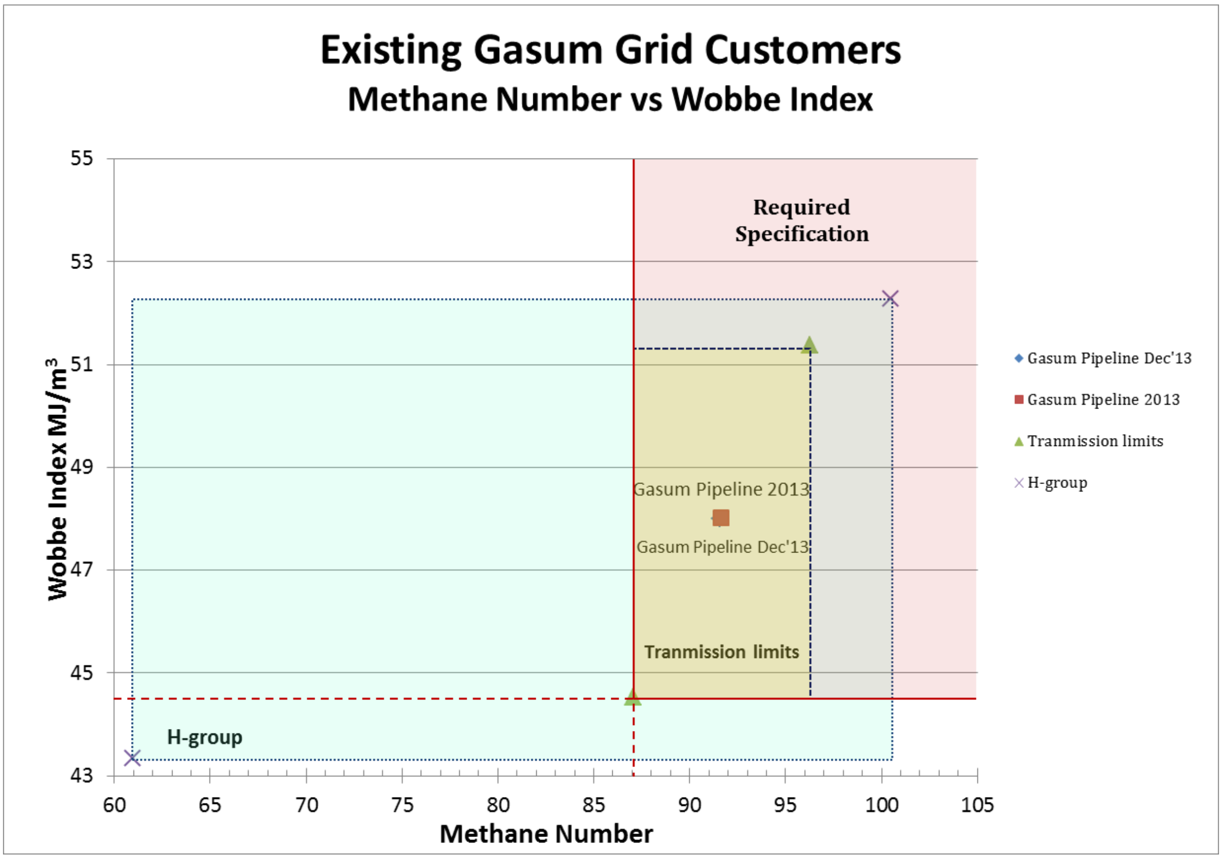




8.5 Appendix-5

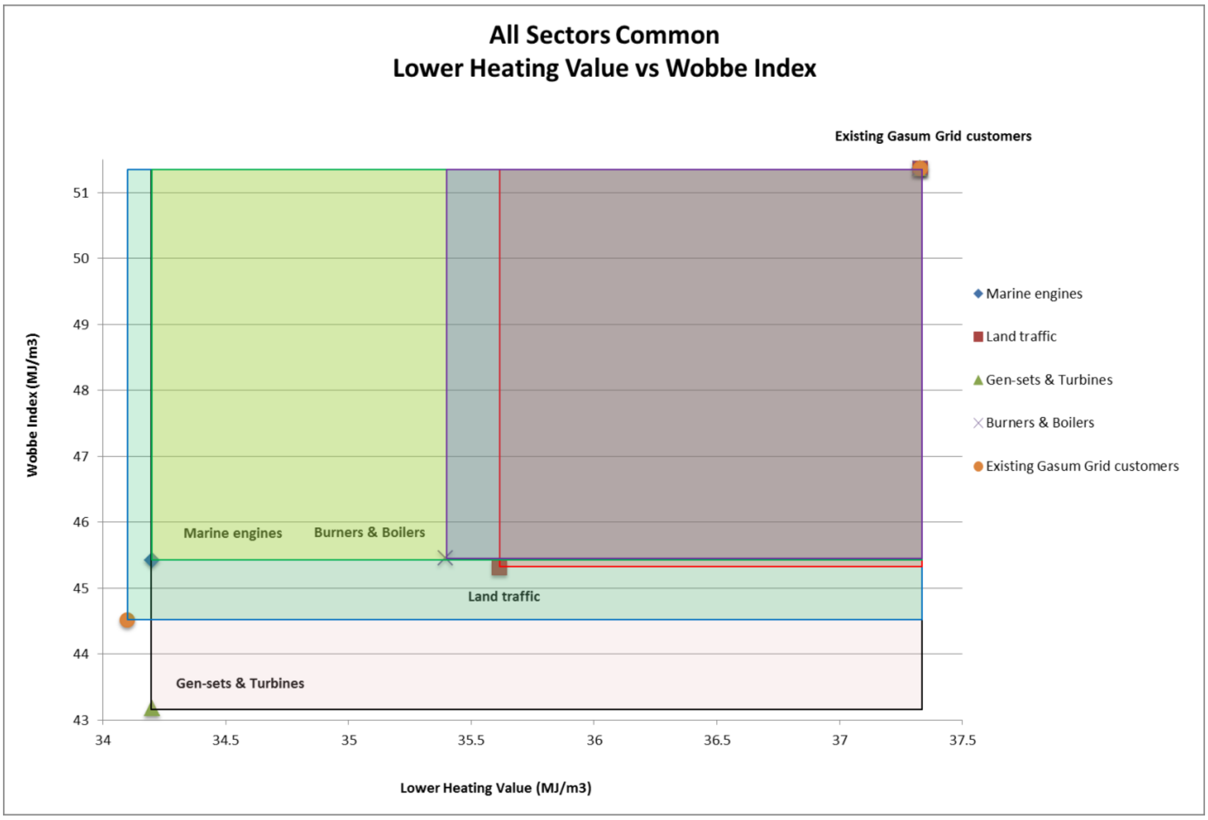
Maps for the Existing Gasum Grid

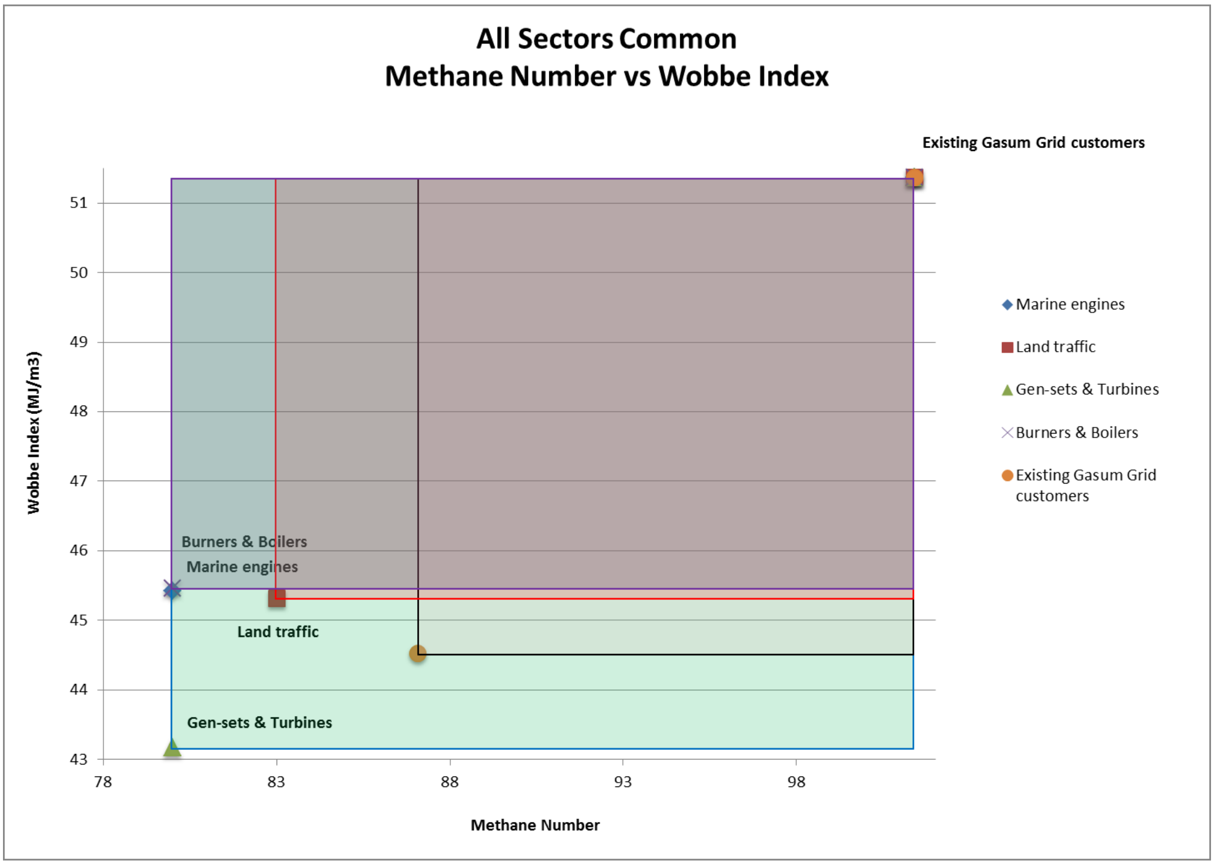




8.6 Appendix-6

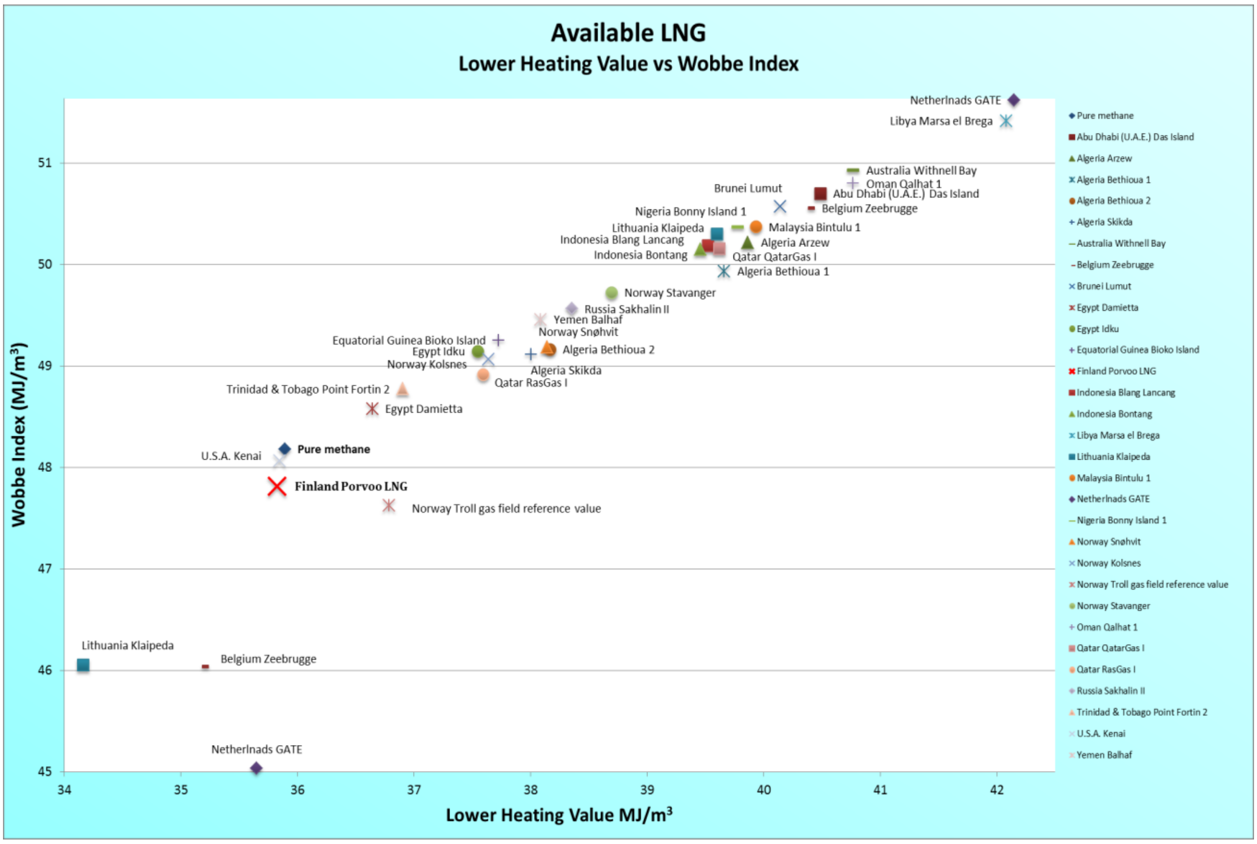
Charts of all sectors defining a common requirement window

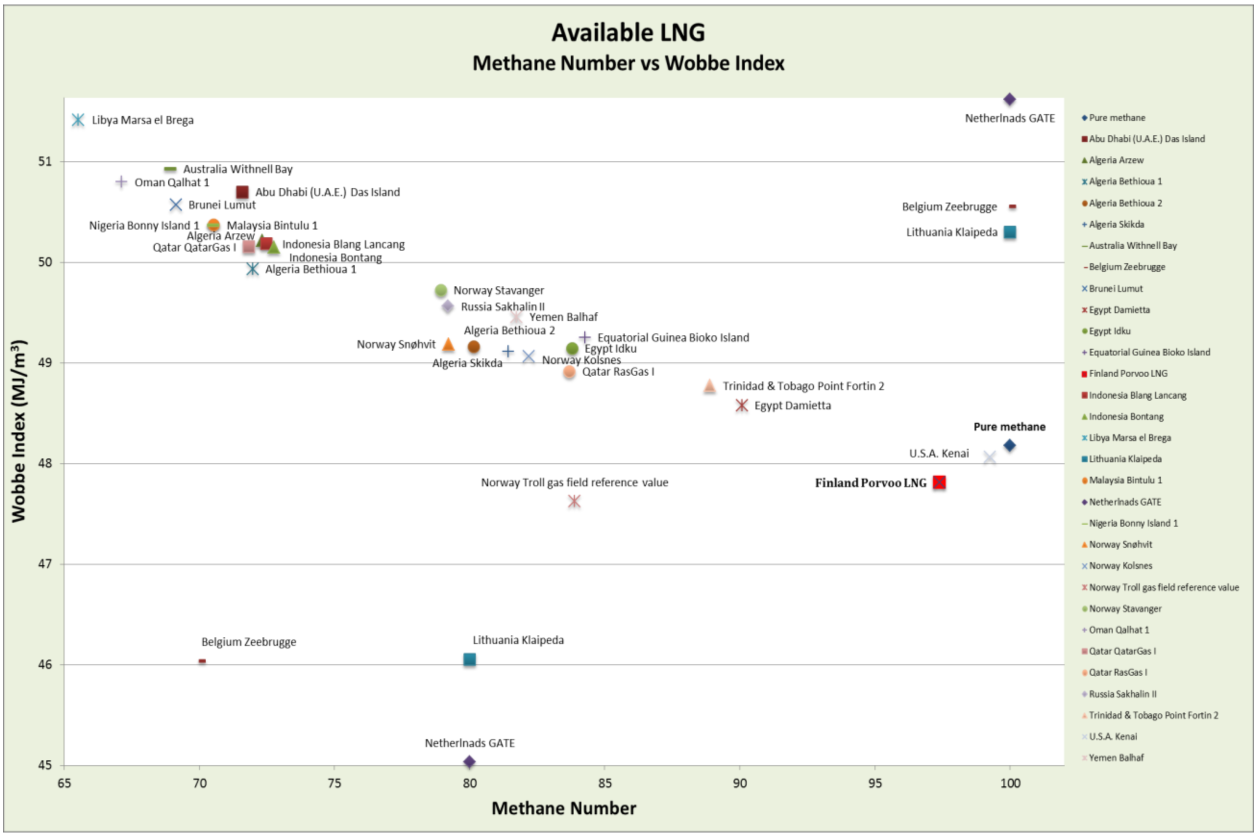




8.7 Appendix-7

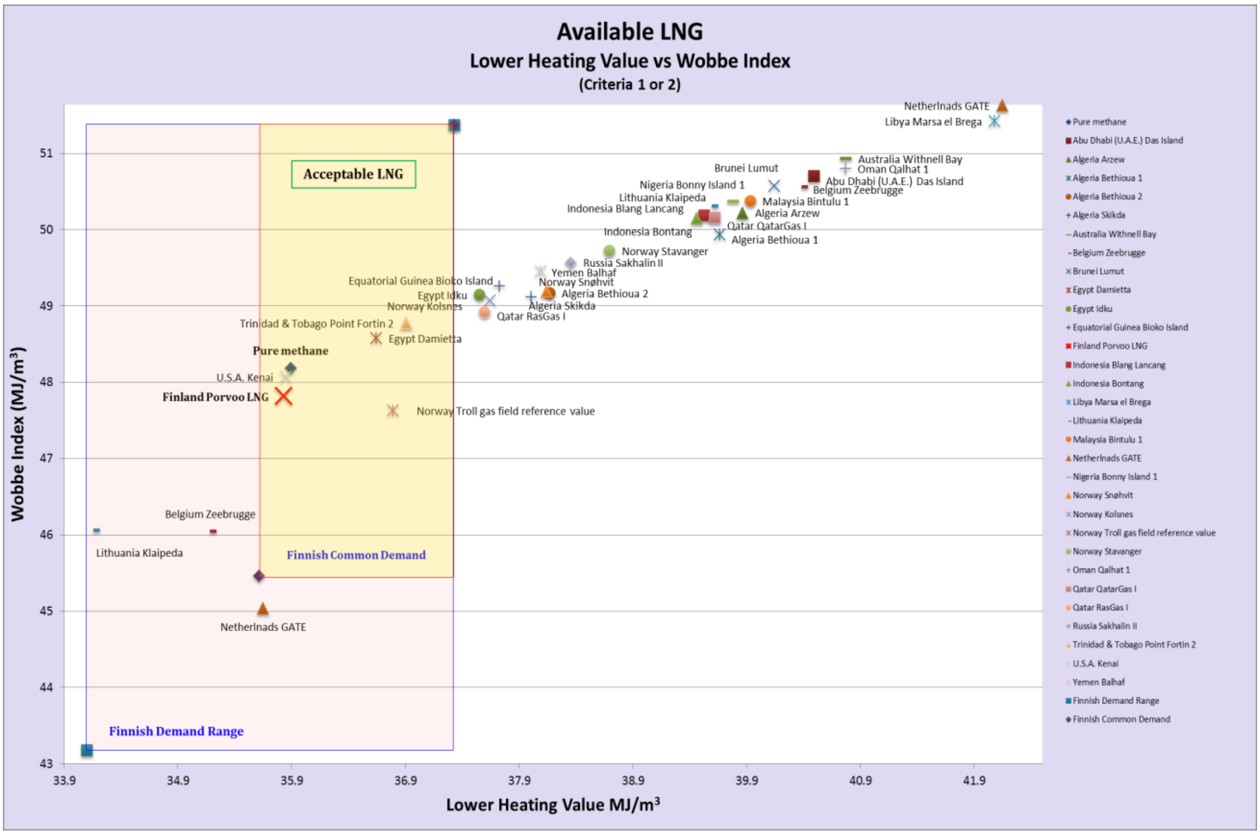
Maps for the Available World LNG Sources and LNG Re-export Terminals

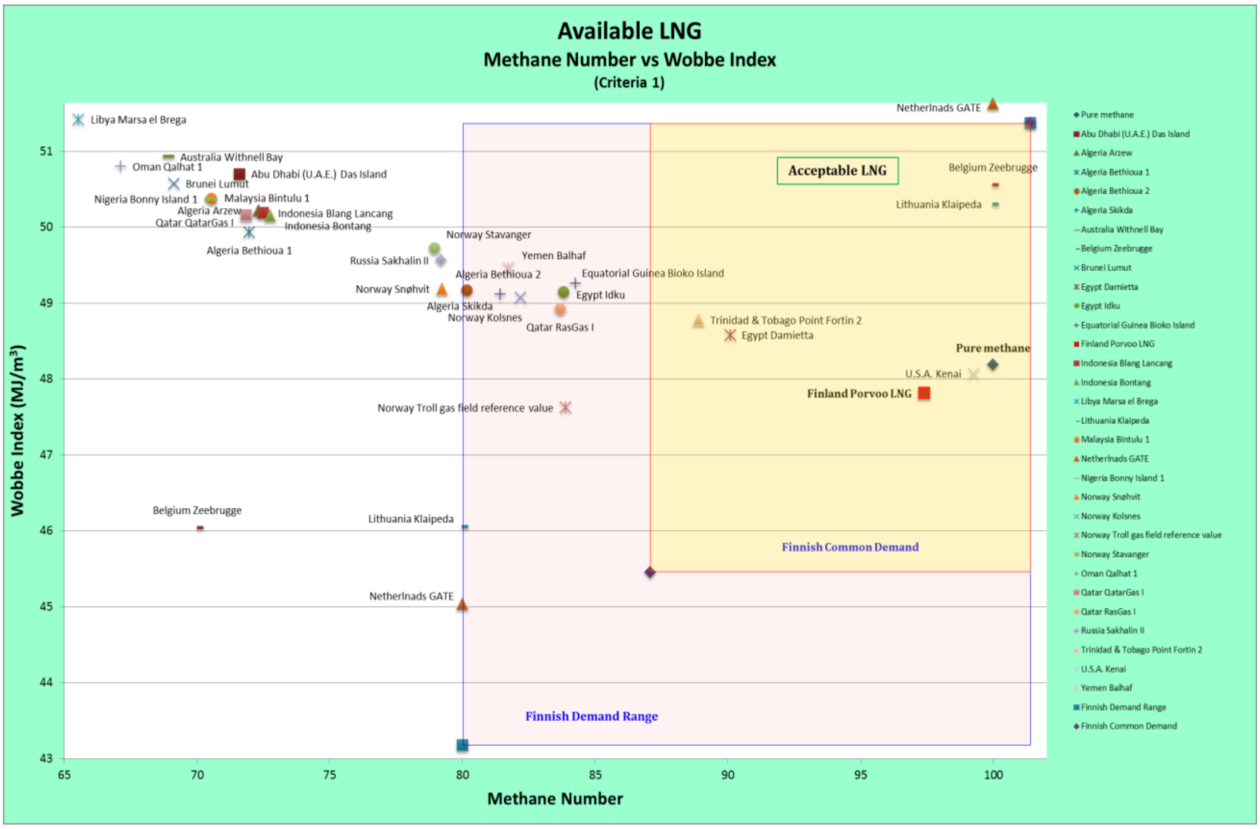




8.8 Appendix-8

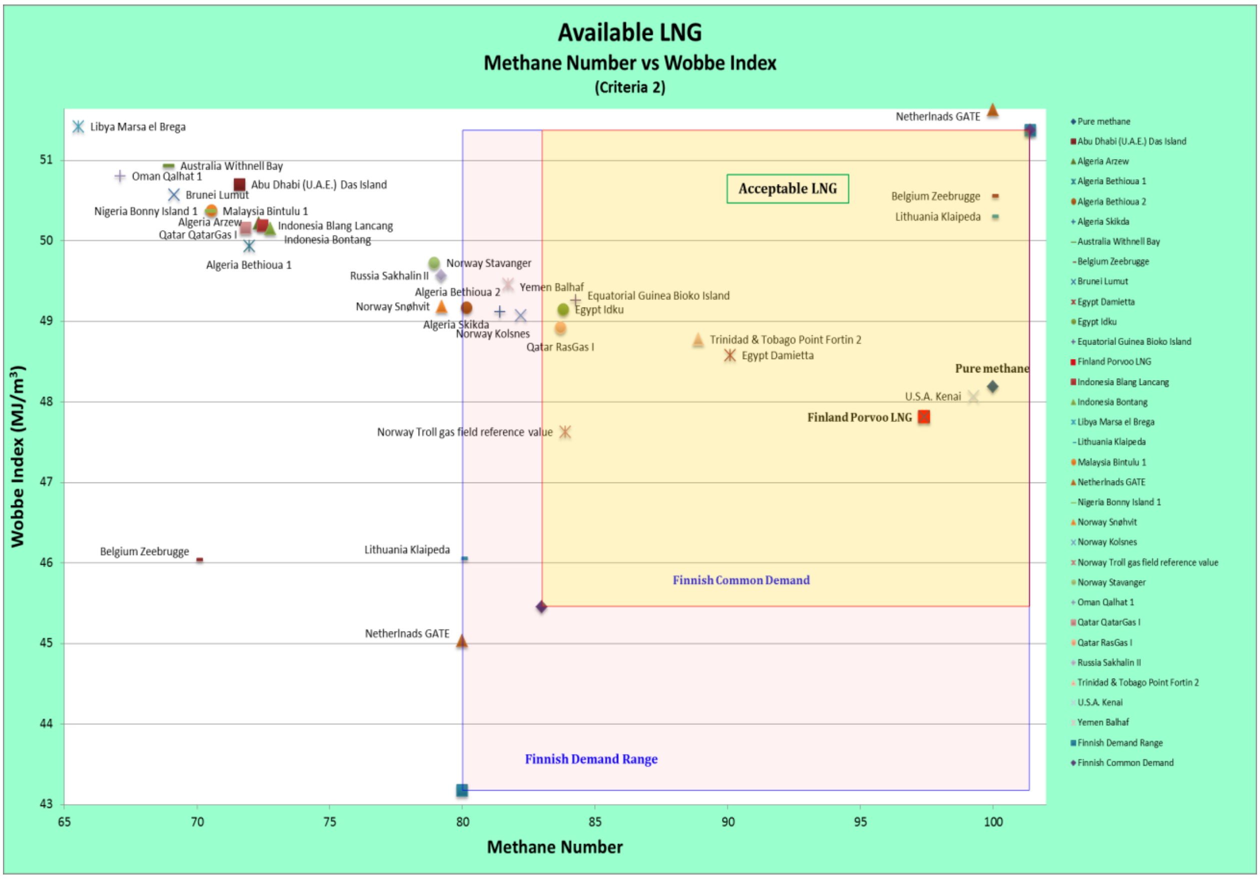
The supply-demand plots for Criteria-1





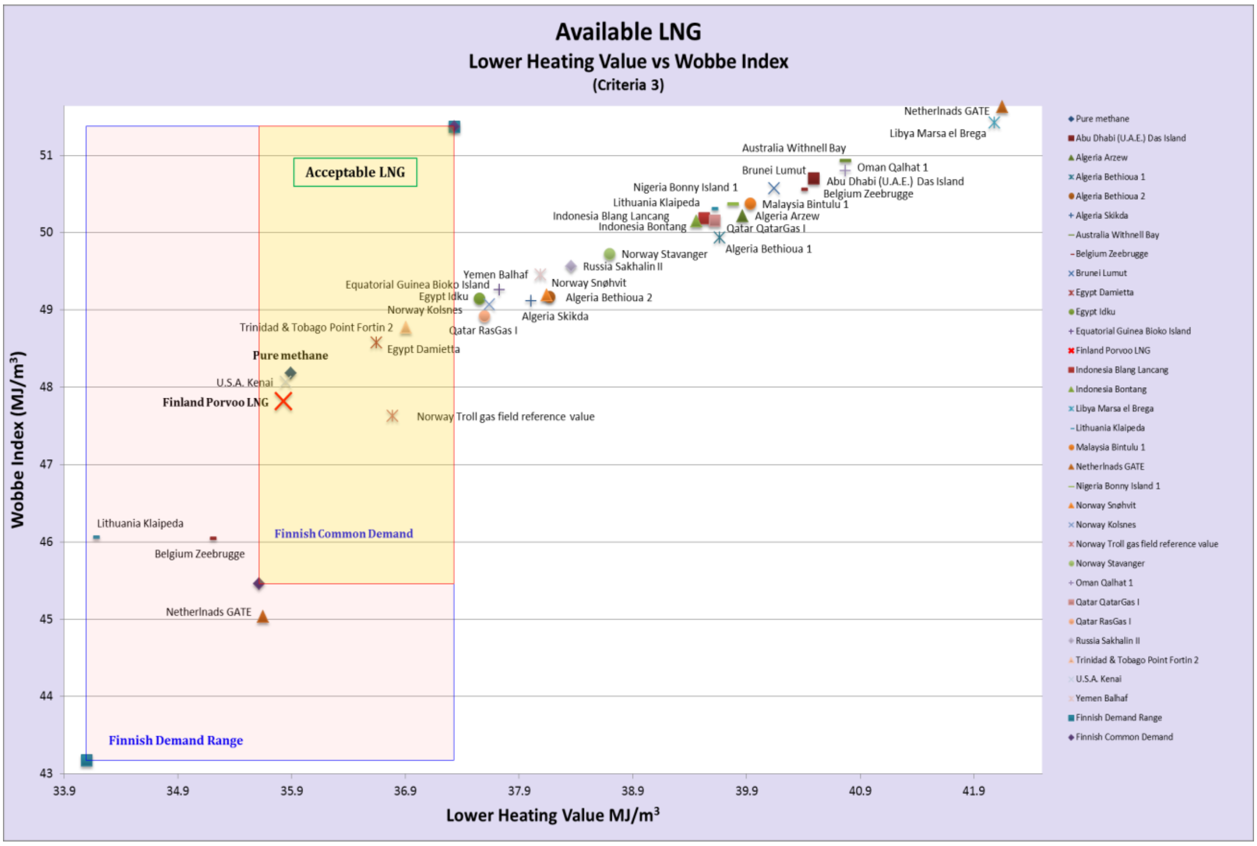
8.9 Appendix-9

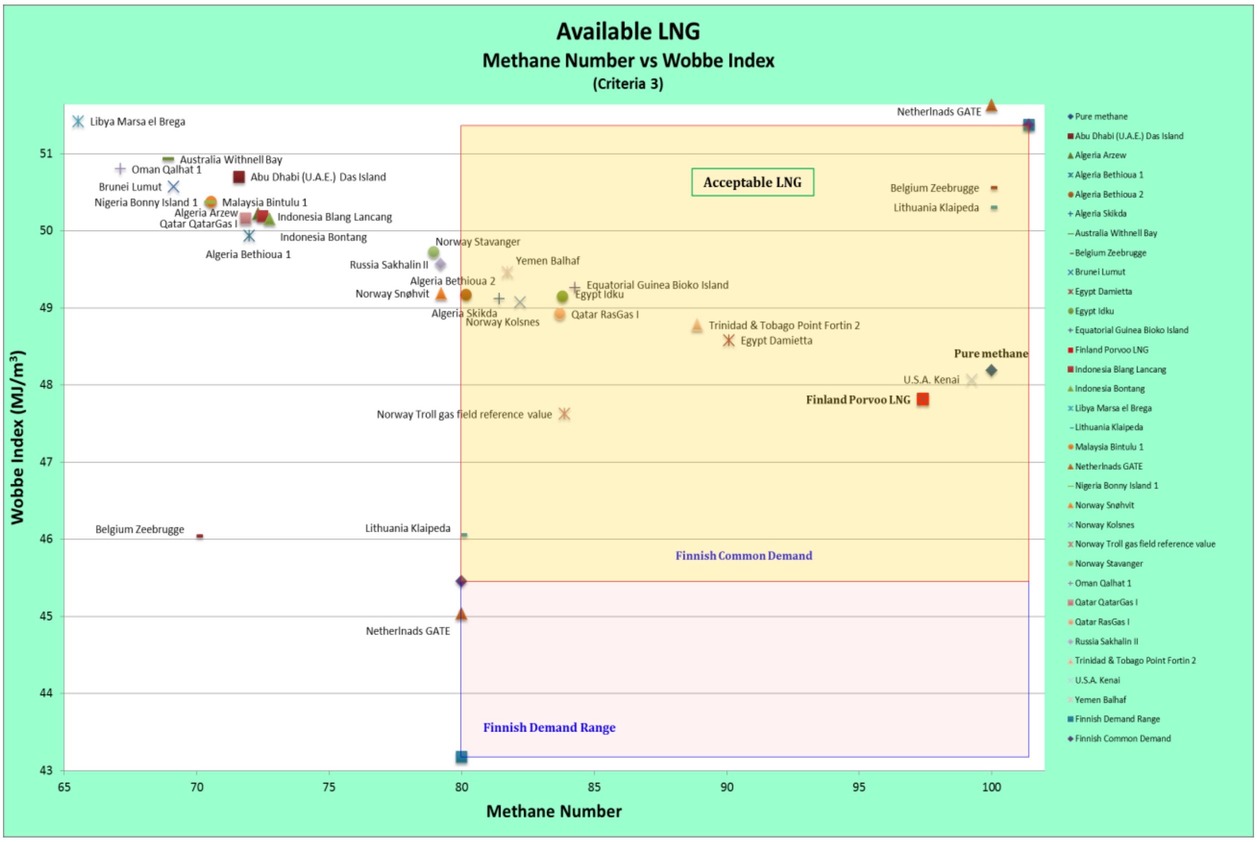
The supply-demand plot for Criteria-2



8.10 Appendix-10

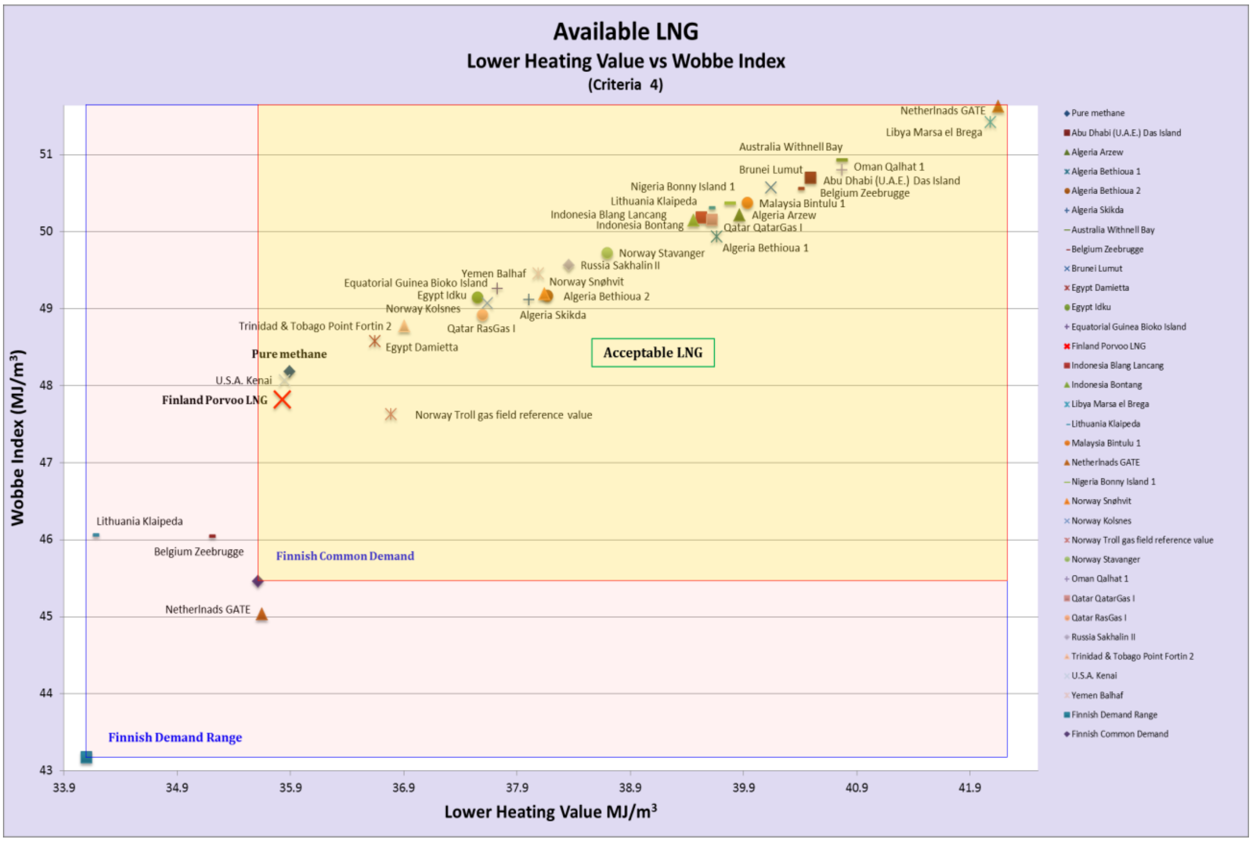
The supply-demand plots for Criteria-3

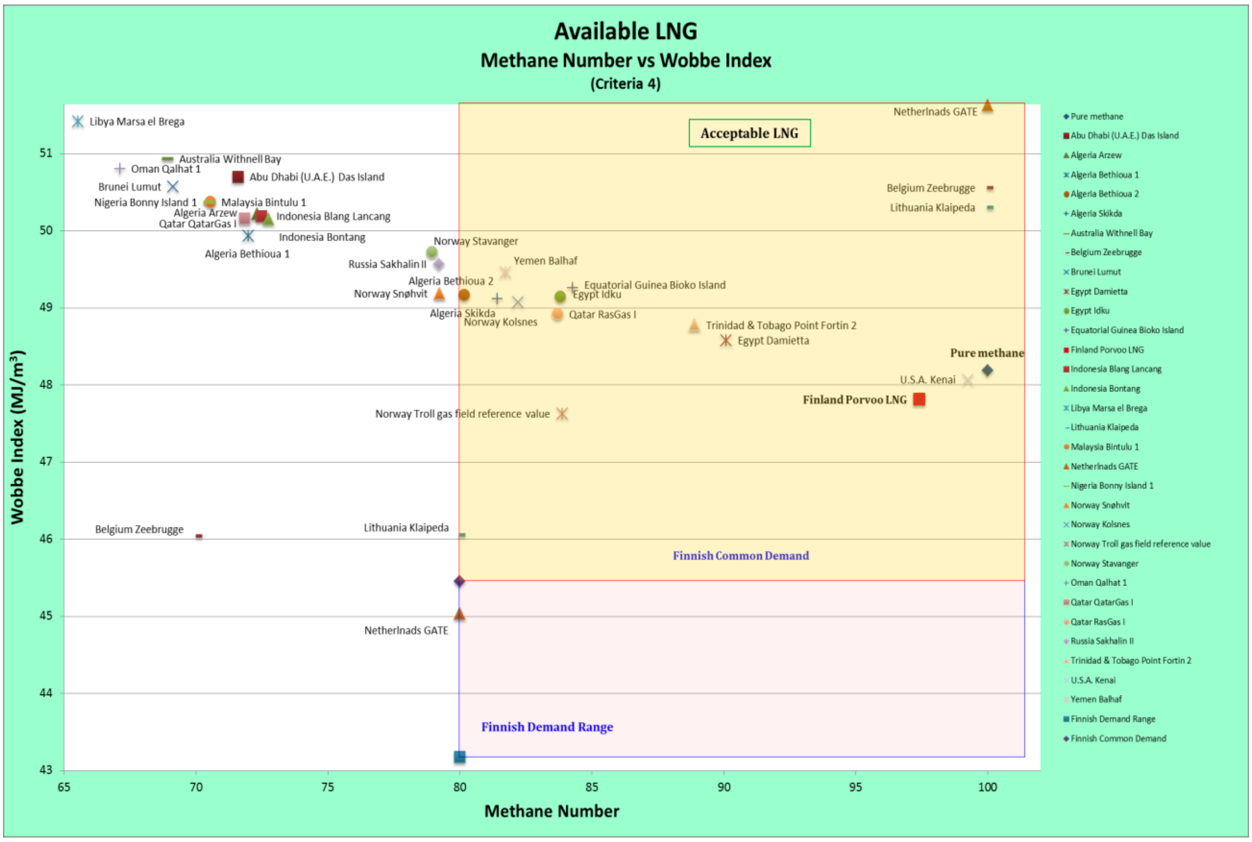




8.11 Appendix-11

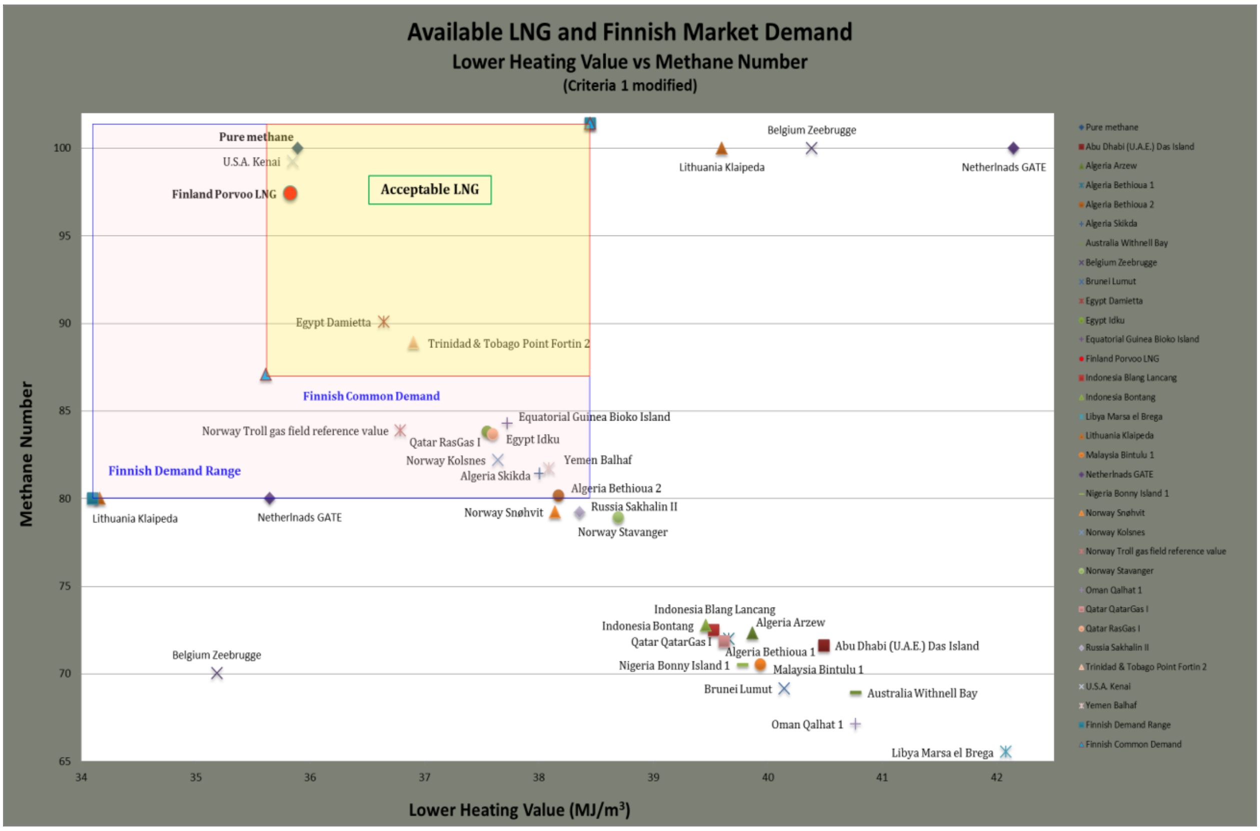
The supply-demand plots for Criteria-4

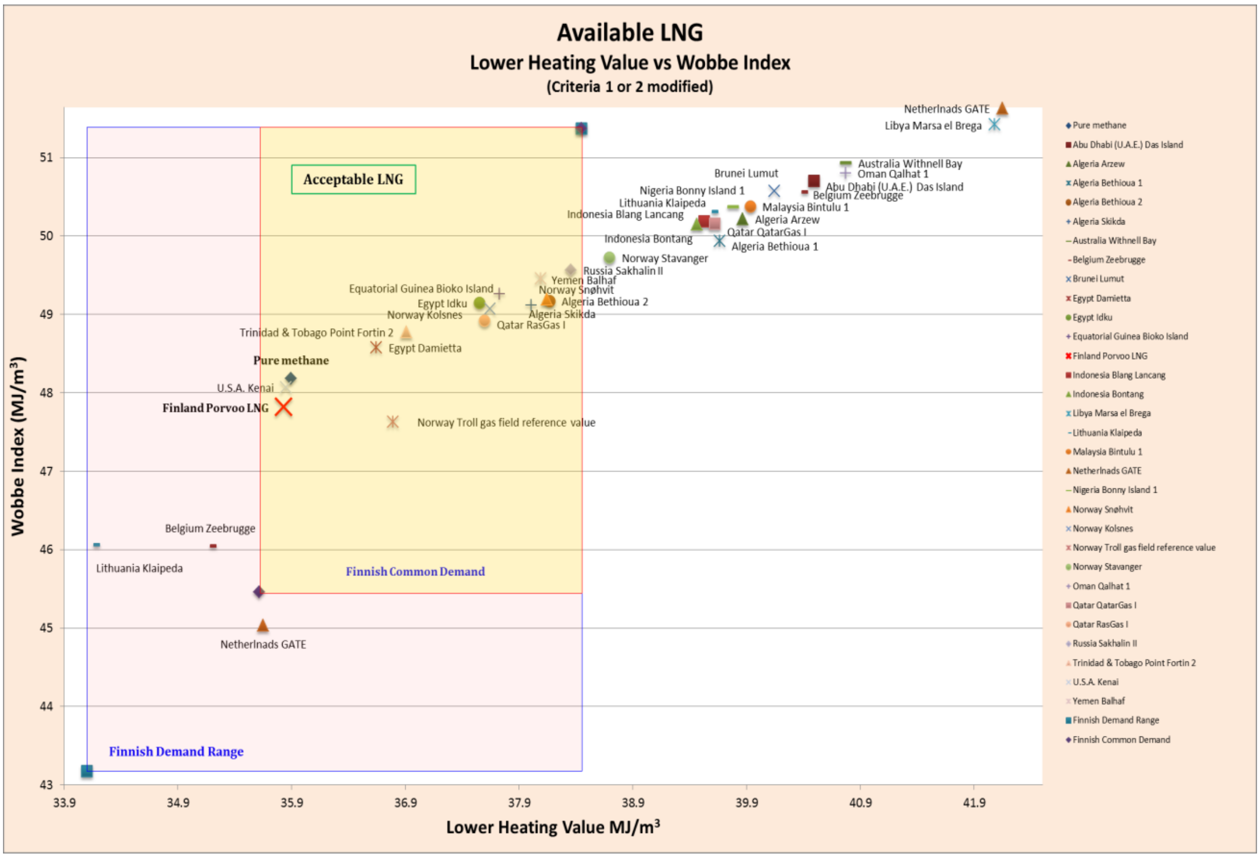




8.12 Appendix-12

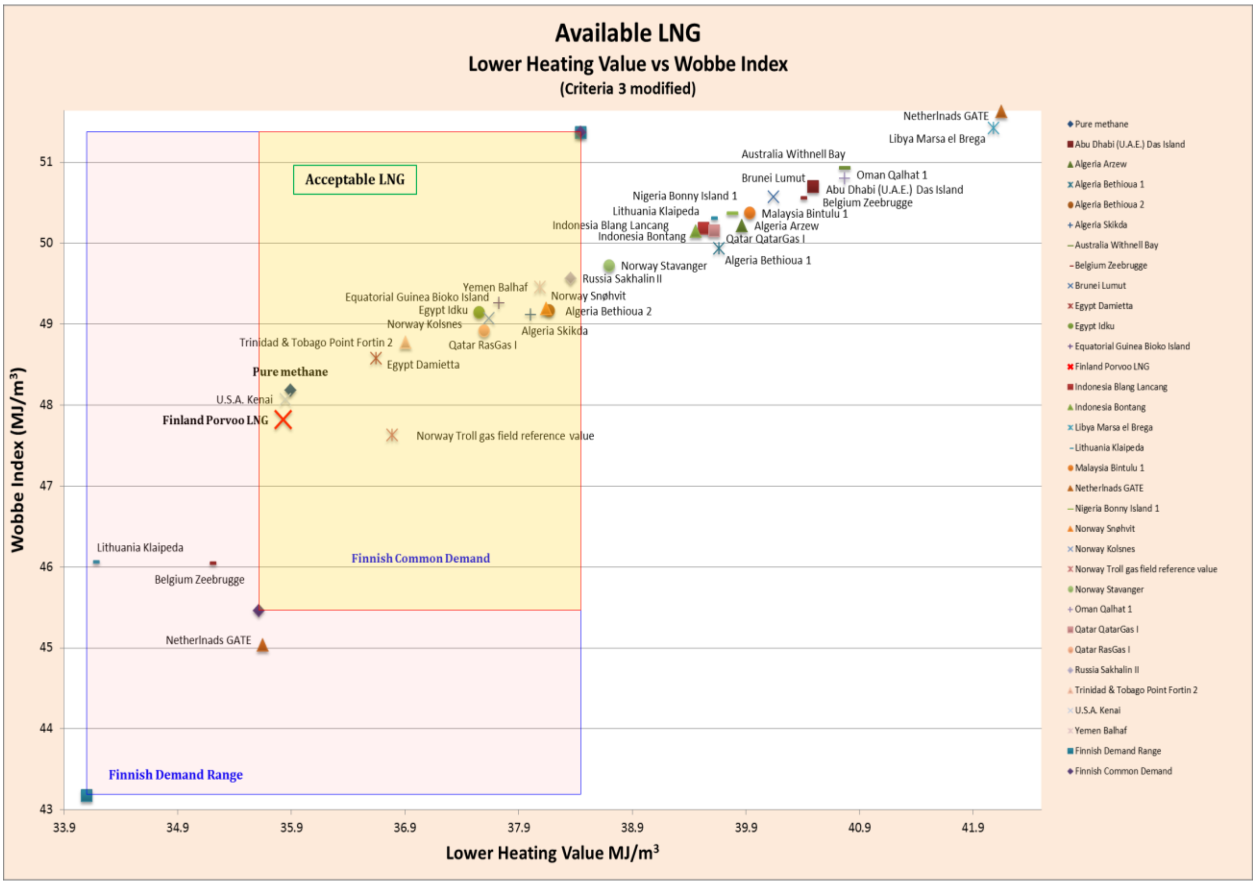
The supply-demand graphs for Modified Criteria-1





8.13 Appendix-13

The supply-demand diagram for Modified Criteria-3



8.14 Appendix-14

Data for sensitivity analysis (Case Study 1) showing the impact of varying LPG extraction on the methane content and yield for the natural gas to be injected into pipeline

State	TEE-100 - Flow Ratio (Flow Ratio_1)	Phase Comp Mole Frac (Overall-Methane)	NG_pipeline - Molar Flow [kgmole/h]
State 1	0	0.911529	97.9806
State 2	0.05	0.915967	97.3818
State 3	0.1	0.920187	96.8066
State 4	0.15	0.924247	96.2124
State 5	0.2	0.928125	95.5962
State 6	0.25	0.931766	94.9546
State 7	0.3	0.935127	94.2924
State 8	0.35	0.93824	93.6179
State 9	0.4	0.94103	92.9322
State 10	0.45	0.943545	92.2406
State 11	0.5	0.945793	91.5469

8.15 Appendix-15

Data for sensitivity analysis (Case Study 3) showing the impact of changing vapour-liquid separation on the methane content and yield for the natural gas to be injected into pipeline

State	q1_LNG - Vapour Fraction	Phase Comp Mole Frac (Overall-Methane)	NG_pipeline - Molar Flow [kgmole/h]
State 1	0.05	0.9549	83.2929
State 2	0.1	0.95428	84.3794
State 3	0.15	0.953728	85.3631
State 4	0.2	0.95309	86.3248
State 5	0.25	0.952338	87.2647
State 6	0.3	0.951338	88.2518
State 7	0.35	0.950188	89.1444
State 8	0.4	0.949107	89.9276
State 9	0.45	0.947574	90.7566
State 10	0.5	0.945809	91.5471

8.16 Appendix-16

aspentech	AALTO UNIVERSITY Burlington, MA USA	Case Name:	LNG_FINALMODEL.HSC
		Unit Set:	SI
		Date/Time:	Sat Mar 15 17:45:32 2014

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		LNG_Feed	BOG	LNG	Liq_BOG	Mixed_LNG
Vapour Fraction		0.0008	1.0000	0.0000	0.0000	0.0000
Temperature	(C)	-161.7 *	-161.7	-161.7	-200.0 *	-161.7
Pressure	(kPa)	101.3 *	101.3	101.3	101.3 *	101.3
Molar Flow	(kgmole/h)	100.0 *	7.866e-002	99.92	7.866e-002	100.0
Mass Flow	(kg/h)	1803	1.368	1801	1.368	1803
Liquid Volume Flow	(m3/h)	5.666	4.048e-003	5.662	4.048e-003	5.666
Heat Flow	(kJ/h)	-9.252e+006	-5720	-9.246e+006	-6516	-9.253e+006
Name		press_LNG	q_LNG	NG	LIQ_lng	q1_LNG
Vapour Fraction		0.0000	0.4500 *	1.0000	0.0000	0.3000 *
Temperature	(C)	-159.7	-71.79	-71.79	-71.79	-67.43
Pressure	(kPa)	4500 *	4500 *	4500	4500	4500 *
Molar Flow	(kgmole/h)	100.0	116.9	52.59	64.28	64.28
Mass Flow	(kg/h)	1803	2216	875.1	1341	1341
Liquid Volume Flow	(m3/h)	5.666	6.785	2.867	3.918	3.918
Heat Flow	(kJ/h)	-9.229e+006	-1.010e+007	-4.233e+006	-5.871e+006	-5.784e+006
Name		V	L	mix_NG	V1	L1
Vapour Fraction		1.0000	0.0000	0.9993	1.0000	0.0000
Temperature	(C)	-67.43	-67.43	-69.51	-61.88	-61.88
Pressure	(kPa)	4500	4500	4500	4500	4500
Molar Flow	(kgmole/h)	19.28	45.00	83.13	11.25	33.75
Mass Flow	(kg/h)	323.3	1017	1389	190.8	826.6
Liquid Volume Flow	(m3/h)	1.058	2.861	4.546	0.6219	2.239
Heat Flow	(kJ/h)	-1.552e+006	-4.232e+006	-6.690e+006	-9.054e+005	-3.267e+006
Name		q2_LNG	M_lng	Recyc_out	L_cond	NG_pipeline
Vapour Fraction		0.2500 *	0.0000	0.0001	0.0000	1.0000
Temperature	(C)	-61.88	-143.4	-61.87 *	-69.51	-69.51
Pressure	(kPa)	4500 *	4500	4500 *	4500	4500
Molar Flow	(kgmole/h)	45.00	116.9	16.87 *	5.857e-002	83.07
Mass Flow	(kg/h)	1017	2216	413.3	1.276	1388
Liquid Volume Flow	(m3/h)	2.861	6.785	1.119	3.653e-003	4.543
Heat Flow	(kJ/h)	-4.172e+006	-1.086e+007	-1.633e+006	-5433	-6.685e+006
Name		Extract_LPG	Recyc			
Vapour Fraction		0.0000	0.0000			
Temperature	(C)	-61.88	-61.88			
Pressure	(kPa)	4500	4500			
Molar Flow	(kgmole/h)	16.87	16.87			
Mass Flow	(kg/h)	413.3	413.3			
Liquid Volume Flow	(m3/h)	1.119	1.119			
Heat Flow	(kJ/h)	-1.633e+006	-1.633e+006			

Compositions

Fluid Pkg: All

Name	LNG_Feed	BOG	LNG	Liq_BOG	Mixed_LNG
Comp Mole Frac (Ethane)	0.0620 *	0.0001	0.0620	0.0001	0.0620
Comp Mole Frac (n-Butane)	0.0100 *	0.0000	0.0100	0.0000	0.0100
Comp Mole Frac (Nitrogen)	0.0040 *	0.1128	0.0039	0.1128	0.0040
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Propane)	0.0230 *	0.0000	0.0230	0.0000	0.0230
Comp Mole Frac (Methane)	0.9010 *	0.8871	0.9010	0.8871	0.9010
Name	press_LNG	q_LNG	NG	LIQ_lng	q1_LNG
Comp Mole Frac (Ethane)	0.0620	0.0827	0.0283	0.1273	0.1273
Comp Mole Frac (n-Butane)	0.0100	0.0167	0.0005	0.0299	0.0299
Comp Mole Frac (Nitrogen)	0.0040	0.0035	0.0057	0.0017	0.0017
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Propane)	0.0230	0.0361	0.0039	0.0625	0.0625
Comp Mole Frac (Methane)	0.9010	0.8610	0.9617	0.7786	0.7786

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Workbook: Case (Main) (continued)

Compositions (continued)

Fluid Pkg: All

Name	V	L	mix_NG	V1	L1
Comp Mole Frac (Ethane)	0.0366	0.1661	0.0328	0.0478	0.2055
Comp Mole Frac (n-Butane)	0.0007	0.0424	0.0006	0.0009	0.0562
Comp Mole Frac (Nitrogen)	0.0036	0.0009	0.0047	0.0022	0.0005
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Propane)	0.0050	0.0871	0.0045	0.0067	0.1139
Comp Mole Frac (Methane)	0.9541	0.7034	0.9573	0.9424	0.6238
Name	**q2_LNG**	**M_lng**	**Recyc_out**	**L_cond**	**NG_pipeline**
Comp Mole Frac (Ethane)	0.1661	0.0827	0.2055 *	0.1492	0.0328
Comp Mole Frac (n-Butane)	0.0424	0.0167	0.0563 *	0.0357	0.0006
Comp Mole Frac (Nitrogen)	0.0009	0.0035	0.0005 *	0.0013	0.0047
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000 *	0.0000	0.0000
Comp Mole Frac (Propane)	0.0871	0.0361	0.1139 *	0.0759	0.0045
Comp Mole Frac (Methane)	0.7034	0.8610	0.6238 *	0.7379	0.9575
Name	**Extract_LPG**	**Recyc**			
Comp Mole Frac (Ethane)	0.2055	0.2055			
Comp Mole Frac (n-Butane)	0.0562	0.0562			
Comp Mole Frac (Nitrogen)	0.0005	0.0005			
Comp Mole Frac (CO2)	0.0000	0.0000			
Comp Mole Frac (Propane)	0.1139	0.1139			
Comp Mole Frac (Methane)	0.6238	0.6238			

Energy Streams

Fluid Pkg: All

Name	Q_bog	Q_press	Q	Q1	Q2
Heat Flow (kJ/h)	-795.2	2.306e+004	7.592e+005	8.666e+004	5.975e+004

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc Level
V-100	Tank	LNG_Feed	LNG BOG	No	500.0 *
Recond	Heater	BOG Q_bog	Liq_BOG	No	500.0 *
Vapourizer	Heater	M_lng Q	q_LNG	No	500.0 *
E-102	Heater	LIQ_lng Q1	q1_LNG	No	500.0 *
E-103	Heater	L Q2	q2_LNG	No	500.0 *
MIX-100	Mixer	Liq_BOG LNG	Mixed_LNG	No	500.0 *
MIX-101	Mixer	V NG V1	mix_NG	No	500.0 *
MIX-102	Mixer	press_LNG Recyc_out	M_lng	No	500.0 *
Sendout_pump	Pump	Mixed_LNG Q_press	press_LNG	No	500.0 *
V-101	Separator	q_LNG	LIQ_lng NG	No	500.0 *
V-102	Separator	q1_LNG	L V	No	500.0 *
V-103	Separator	q2_LNG	L1 V1	No	500.0 *
V-104	Separator	mix_NG	L_cond NG_pipeline	No	500.0 *
RCY-1	Recycle	Recyc	Recyc_out	No	3500 *
TEE-100	Tee	L1	Extract_LPG Recyc	No	500.0 *

8.17 Appendix-17

aspentech	AALTO UNIVERSITY Burlington, MA USA	Case Name:	2nd process_LNG.hsc
		Unit Set:	SI
		Date/Time:	Thu Mar 20 21:20:24 2014

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		BOG	LNG	Liq_BOG	Mixed_LNG	press_LNG
Vapour Fraction		1.0000	0.0000	0.0000	0.0394	0.0000
Temperature	(C)	-161.7	-161.7	-270.0 *	-176.5	-174.8
Pressure	(kPa)	101.3	101.3	103.0 *	101.3	4500 *
Molar Flow	(kgmole/h)	7.866e-002	99.92	10.64	110.6	106.2
Mass Flow	(kg/h)	1.368	1801	286.7	2088	1977
Liquid Volume Flow	(m3/h)	4.048e-003	5.662	0.3873	6.049	5.881
Heat Flow	(kJ/h)	-5720	-9.246e+006	-2.488e+005	-9.495e+006	-9.380e+006
Name		LNG_Feed	Nitrogen	BOG_Nit	L	V
Vapour Fraction		0.0008	1.0000 *	1.0000	0.0000	1.0000
Temperature	(C)	-161.7 *	-172.9	-181.6	-176.5	-176.5
Pressure	(kPa)	101.3 *	800.0 *	101.3	101.3	101.3
Molar Flow	(kgmole/h)	100.0 *	6.200 *	10.64	106.2	4.352
Mass Flow	(kg/h)	1803	173.7	286.7	1977	111.5
Liquid Volume Flow	(m3/h)	5.666	0.2154	0.3873	5.881	0.1676
Heat Flow	(kJ/h)	-9.252e+006	-3.763e+004	-1.349e+005	-9.403e+006	-9.159e+004
Name		Vap_recycle	NG_pipeline			
Vapour Fraction		1.0000	1.0000 *			
Temperature	(C)	-176.5 *	-28.45			
Pressure	(kPa)	101.3 *	4500 *			
Molar Flow	(kgmole/h)	4.359 *	106.2			
Mass Flow	(kg/h)	111.7	1977			
Liquid Volume Flow	(m3/h)	0.1678	5.881			
Heat Flow	(kJ/h)	-9.151e+004	-7.994e+006			

Compositions

Fluid Pkg: All

Name	BOG	LNG	Liq_BOG	Mixed_LNG	press_LNG
Comp Mole Frac (Ethane)	0.0001	0.0620	0.0000	0.0561	0.0584
Comp Mole Frac (n-Butane)	0.0000	0.0100	0.0000	0.0090	0.0094
Comp Mole Frac (Nitrogen)	0.1128	0.0039	0.9116	0.0912	0.0622
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Propane)	0.0000	0.0230	0.0000	0.0208	0.0217
Comp Mole Frac (Methane)	0.8871	0.9010	0.0884	0.8228	0.8483
Comp Mole Frac (Air)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	LNG_Feed	Nitrogen	BOG_Nit	L	V
Comp Mole Frac (Ethane)	0.0620 *	0.0000 *	0.0000	0.0584	0.0000
Comp Mole Frac (n-Butane)	0.0100 *	0.0000 *	0.0000	0.0094	0.0000
Comp Mole Frac (Nitrogen)	0.0040 *	1.0000 *	0.9116	0.0622	0.7995
Comp Mole Frac (CO2)	0.0000 *	0.0000 *	0.0000	0.0000	0.0000
Comp Mole Frac (Propane)	0.0230 *	0.0000 *	0.0000	0.0217	0.0000
Comp Mole Frac (Methane)	0.9010 *	0.0000 *	0.0884	0.8483	0.2005
Comp Mole Frac (Air)	0.0000 *	0.0000 *	0.0000	0.0000	0.0000
Name	Vap_recycle	NG_pipeline			
Comp Mole Frac (Ethane)	0.0000 *	0.0584			
Comp Mole Frac (n-Butane)	0.0000 *	0.0094			
Comp Mole Frac (Nitrogen)	0.8002 *	0.0622			
Comp Mole Frac (CO2)	0.0000 *	0.0000			
Comp Mole Frac (Propane)	0.0000 *	0.0217			
Comp Mole Frac (Methane)	0.1998 *	0.8483			
Comp Mole Frac (Air)	0.0000 *	0.0000			

Energy Streams

Fluid Pkg: All

Name		Q_bog	Q_press	Q_vap		
Heat Flow	(kJ/h)	-1.139e+005	2.322e+004	1.386e+006		

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc Level
V-100	Tank	LNG_Feed	LNG	No	500.0 *

* Specified by user.

Workbook: Case (Main) (continued)

Unit Ops (continued)

Operation Name	Operation Type	Feeds	Products	Ignored	Calc Level
V-100	Tank		BOG	No	500.0 *
Recond	Heater	BOG_Nit	Liq_BOG	No	500.0 *
		Q_bog			
E-100	Heater	press_LNG	NG_pipeline	No	500.0 *
		Q_vap			
MIX-100	Mixer	Liq_BOG	Mixed_LNG	No	500.0 *
		LNG			
MIX-101	Mixer	Nitrogen	BOG_Nit	No	500.0 *
		BOG			
		Vap_recycle			
Sendout_pump	Pump	L	press_LNG	No	500.0 *
		Q_press			
V-101	Separator	Mixed_LNG	L	No	500.0 *
			V		
RCY-1	Recycle	V	Vap_recycle	No	3500 *

* Specified by user.

8.18 Appendix-18

AALTO UNIVERSITY Burlington, MA USA	Case Name:	3rd process_LNG.hsc
	Unit Set:	SI
	Date/Time:	Thu Mar 20 22:29:53 2014

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		LNG_Feed	BOG	LNG	Liq_BOG	Mixed_LNG
Vapour Fraction		0.0008	1.0000	0.0000	0.0000	0.0000
Temperature	(C)	-161.7 *	-161.7	-161.7	-270.0 *	-176.8
Pressure	(kPa)	101.3 *	101.3	101.3	103.0 *	101.3
Molar Flow	(kgmole/h)	100.0 *	7.866e-002	99.92	6.234	106.2
Mass Flow	(kg/h)	1803	1.368	1801	272.2	2074
Liquid Volume Flow	(m3/h)	5.666	4.048e-003	5.662	0.3323	5.994
Heat Flow	(kJ/h)	-9.252e+006	-5720	-9.246e+006	-2.662e+006	-1.191e+007
Name		press_LNG	CO2	BOG_CO2	NG_pipeline	
Vapour Fraction		0.0000	1.0000 *	1.0000	1.0000 *	
Temperature	(C)	-175.2	-75.54	-78.76	-27.46	
Pressure	(kPa)	4500 *	200.0 *	101.3	4500 *	
Molar Flow	(kgmole/h)	106.2	6.155 *	6.234	106.2	
Mass Flow	(kg/h)	2074	270.9	272.2	2074	
Liquid Volume Flow	(m3/h)	5.994	0.3282	0.3323	5.994	
Heat Flow	(kJ/h)	-1.189e+007	-2.447e+006	-2.453e+006	-1.043e+007	

Compositions

Fluid Pkg: All

Name	LNG_Feed	BOG	LNG	Liq_BOG	Mixed_LNG
Comp Mole Frac (Ethane)	0.0620 *	0.0001	0.0620	0.0000	0.0584
Comp Mole Frac (n-Butane)	0.0100 *	0.0000	0.0100	0.0000	0.0094
Comp Mole Frac (Nitrogen)	0.0040 *	0.1128	0.0039	0.0014	0.0038
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.9874	0.0580
Comp Mole Frac (Propane)	0.0230 *	0.0000	0.0230	0.0000	0.0217
Comp Mole Frac (Methane)	0.9010 *	0.8871	0.9010	0.0112	0.8488
Comp Mole Frac (Air)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Name	press_LNG	CO2	BOG_CO2	NG_pipeline	
Comp Mole Frac (Ethane)	0.0584	0.0000 *	0.0000	0.0584	
Comp Mole Frac (n-Butane)	0.0094	0.0000 *	0.0000	0.0094	
Comp Mole Frac (Nitrogen)	0.0038	0.0000 *	0.0014	0.0038	
Comp Mole Frac (CO2)	0.0580	1.0000 *	0.9874	0.0580	
Comp Mole Frac (Propane)	0.0217	0.0000 *	0.0000	0.0217	
Comp Mole Frac (Methane)	0.8488	0.0000 *	0.0112	0.8488	
Comp Mole Frac (Air)	0.0000	0.0000 *	0.0000	0.0000	

Energy Streams

Fluid Pkg: All

Name		Q_bog	Q_press	Q_vap		
Heat Flow	(kJ/h)	-2.094e+005	2.288e+004	1.453e+006		

Unit Ops

Operation Name	Operation Type	Feeds	Products	Ignored	Calc Level
V-100	Tank	LNG_Feed	LNG BOG	No	500.0 *
Recond	Heater	BOG_CO2 Q_bog	Liq_BOG	No	500.0 *
E-100	Heater	press_LNG Q_vap	NG_pipeline	No	500.0 *
MIX-100	Mixer	Liq_BOG LNG	Mixed_LNG	No	500.0 *
MIX-101	Mixer	CO2 BOG	BOG_CO2	No	500.0 *
Sendout_pump	Pump	Mixed_LNG Q_press	press_LNG	No	500.0 *

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